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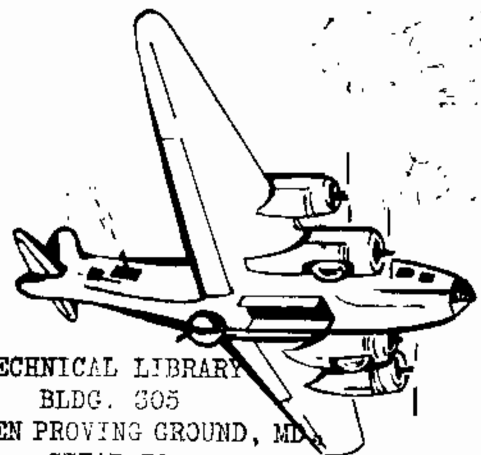
ORDNANCE DEPARTMENT

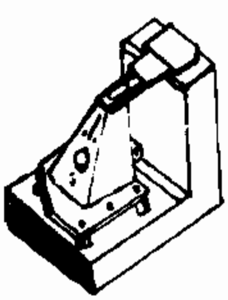
BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MD.



MEMORANDUM
REPORT No. 484

Effectiveness of Incendiary Ammunition Against Aircraft Fuel Tanks



Arthur Stein
Mary Gene Torsch

[redacted]

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Effectiveness of Incendiary Ammunition Against Aircraft Fuel Tanks

MEMORANDUM
REPORT No. 484

PROJECT NO. TB3-0238A OF THE RESEARCH AND DEVELOPMENT DIVISION, ORDNANCE DEPARTMENT

Arthur Stein

Mary Gene Torsch

5 OCTOBER 1948

ORDNANCE DEPARTMENT
BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MD.

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BALLISTIC RESEARCH LABORATORIES

MEMORANDUM REPORT NO. 484

Stein/Torch/mne
Aberdeen Proving Ground, Md.
11 August 1948

EFFECTIVENESS OF INCENDIARY AMMUNITION AGAINST AIRCRAFT FUEL TANKS

ABSTRACT

The probability of obtaining a kill on an aircraft due to the vulnerability of its fuel system to incendiary projectiles is the product of the probability that a round perforates the tank, the probability that the projectile functions, the probability that the penetrating projectile ignites the fuel after functioning and perforating, the probability that the tank does not self-seal and the probability that a resulting fire causes a kill to the aircraft. These various probabilities have been obtained as functions of striking velocity from firings of incendiary ammunition against gasoline and kerosene filled fuel tanks. Experiments under controlled conditions, designed to study the mechanics of fuel tank ignition, are described and preliminary results presented. A formula is given which utilizes the tabulated data to give the total probability of fuel tank fire in "n" hits on the plane as a function of both the single-shot probability of fire and the probability of fire due to impacting an already leaking fuel cell.

[redacted]

INTRODUCTION

One of the most economical methods of obtaining killing damage to an aircraft is by liberating destructively the energy contained within the fuel it carries.

This report presents results obtained to date in all firings against aircraft fuel systems conducted at Aberdeen Proving Ground in the current vulnerability firings, with the exception of fragment damage. Additional firings are now in progress and much analysis remains to be done. Current tests include firings of bare TNT and also of shaped charges against aircraft fuel cells. The current program also proposes to analyse the mechanism of fuel tank ignition through study of the fuel tank spray, duration and type of projectile functioning, the effect of altitude and speed of aircraft and the effect of changes in type of fuel and in fuel tank and line construction. Partial results of the current program are presented in this report. The study of fuel tank damage by fragments is in progress and will be separately treated.

The factors affecting fuel tank ignition are quite varied and many have been studied at other agencies. Those studies most pertinent to the present report have been cited.

Probably the best available reference on the history, design, development and characteristics of incendiary ammunition is the volume issued by the Office, Chief of Ordnance.[1] In addition to detailed description of all of the incendiary ammunition developed by the Ordnance Department, and discussion of test results, this report contains an exhaustive list of references, particularly to hundreds of Ordnance Committee Meeting items and firing records which could not otherwise be located in a reasonable length of time.

FUEL TANK IGNITION BY INCENDIARY AMMUNITION

The purpose of the firings against the aircraft target is to evaluate the vulnerability, not of these particular aircraft, but of aircraft of the future. Hence, the data to be obtained must be in a form which will permit evaluation of the vulnerability of many types of fuel tank installations. The following remarks indicate a manner in which this may be done.

The net single-shot probability of obtaining an "A" kill[2] due to ignition of a particular fuel tank or cell, for a random hit on the plane, is

$$P_{A_F} = (P\ H/\text{plane})\ (P\ CP/H)\ (P\ fcn/CP)\ (P\ F/fcn,\ CP)\ (P\ A/F),$$

[1] Record of Army Ordnance Research and Development, Volume 2, Small Arms and Small Arms Ammunition, Book 2 Small Arms Ammunition (C).

[2] An "A" kill is one which causes the aircraft to fall within five minutes. Complete definition of the different categories under which damage is assessed at Aberdeen are to be found in BRL 462 "Aircraft Vulnerability and Overall Armament Effectiveness."

where[1]

(P H/plane = probability of hitting the projected area of the tank if the plane is hit,

(P CP/H = probability of a cell wall perforation if the projected area of the cell is hit,

(P fcn/CP) = probability that a round functions, i.e., itself ignites,

(P F/fcn, CP) = probability of igniting a fuel cell if the round functions (and perforates) the cell,

(P A/F) = probability of an "A" kill on the plane if the fuel is ignited.

The corresponding expression for so-called "compound" damage, the probability of obtaining an "A" kill by an impact into a previously damaged and leaking tank, is developed in a previous report,[2] and presented in Appendix B.

The several factors in the foregoing expression for the net probability of obtaining an "A" kill, vary differently with change in striking velocity. It is evident that the probability of an "A" kill on any aircraft due to fuel tank fire is not obtainable solely from field firings against aircraft.

The factor (P H/plane) is equal to the relative projected area of the fuel tank, which area is obtained in the current effectiveness studies at Aberdeen by planimetering photographs of skeletal models. Figure 1 is such a photograph of the XB-47 jet bomber.

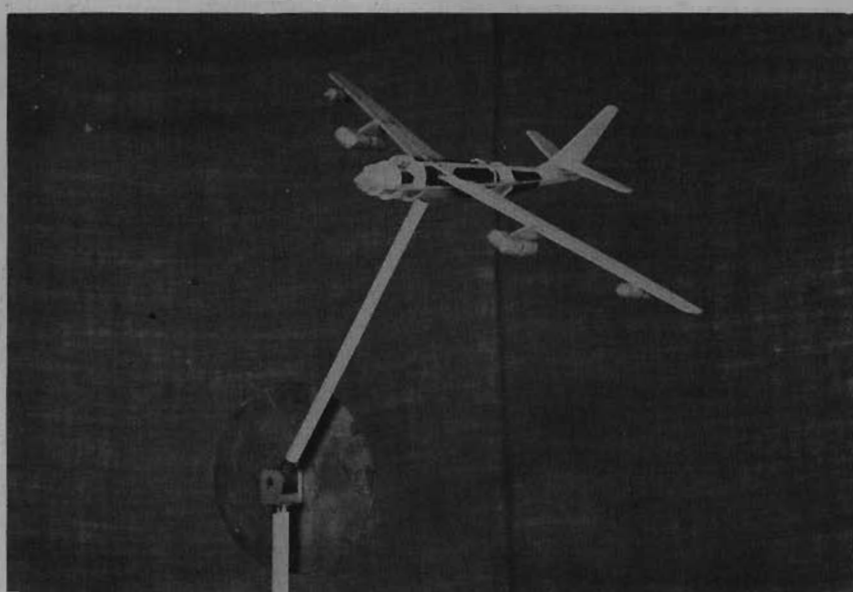

FIG. 1 Optimum Caliber Program. View of XB-47 Model simulating range of 185 yards.

[1]Thus, if (P H/plane) = .05, (P CP/H) = .90, (P fcn/CP) = .80, P F/fcn, CP) = .20 and (P A/F) = .50, then the net single-shot probability, P_{A_F} = .0036. The probability of an "A" kill due to fire in the target tank for 20 random hits on the plane is then = $1 - e^{-20(.0036)}$ = .07.

[2]BRL Memorandum Report No. 437. "Optimum Caliber Program," 1 July 1946.

The probability (P CP/H), of a cell perforation if the projected area of the tank is hit, is obtained both from field firings and also, when fuel cells are masked by heavy dural or armor plate, by means of theoretical penetration laws. The field firings have been conducted against a large variety of fuel tank installations and consequently an installation will have been used as a target which is not significantly different from the installation on a plane under study. The sample number for the field firings is larger for the determination of (P CP/H) than for P F/fcn, CP) or (P A/F) since the same data for (P CP/H) apply equally for gasoline or kerosene filled cells and for single-shot and compound hits.

The factor (P fcn/CP), the probability that a round which penetrates the cell has functioned, also does not depend on the type of fuel or on whether there was previous leakage in the area. Consequently, here too it has been possible to obtain a relatively large sample size from the field firings.

It should be emphasized that the probability of functioning does not of itself adequately describe the contribution to fuel tank ignition of the functioning characteristics of the ammunition. This is true even when data is available describing the variation in the probability of functioning with variations of striking velocity, spin, obliquity, target thickness and composition. Two types of projectiles may have the same probability of functioning but may differ markedly in how the functioning occurs. Important differences may be found in the distance from the target plate (or wing skin) to the initial point of functioning and in the length, intensity and duration of flash produced. There is in progress a series of firings, proposed by Mr. F. E. Watts of A & A Division, Development and Proof Services, Aberdeen Proving Ground, of various types of incendiary ammunition to determine its functioning against dural plate of various thicknesses. These firings are being conducted over a wide range of striking velocities and for impacts on the plate at several obliquities. A short summary of preliminary results appears in a later section herein on results of supplementary tests.

The probability (P F/fcn, CP), that a projectile which functions and perforates a fuel cell wall will ignite the contents, depends markedly on the type of fuel and on whether there was any previous leakage in the area. A study of the mechanism of ignition involves consideration of the striking velocity and mass of the projectile, the position, degree and duration of the incendiary functioning, the manner in which the nose of the projectile is blunted when it strikes the aircraft skin, the delay before spray emerges from the tank after impact, the degree of this spray, the size, shape and self-sealing properties of the tank, the amount and type of fuel it contains, the location of the impact on the tank and the environmental conditions such as altitude, temperature, confinement of space about tank, location of tank in wing, protection of hole in tank from the effects of the slip-stream, structural material which is inflammable, and the like.

The effects of variations in the factors affecting fuel cell ignition are currently being studied under more controlled conditions than are possible by the firing against aircraft targets. The progress made to date in these studies in indicated in a later section on supplementary tests.

The last factor, (P A/F), is the probability that the ignited tank will cause an "A" kill on the plane (and similarly for "B", "C" and "E" damage). This factor depends on the amount of fuel feeding the fire and on the location and function of the tank in the fuel system. For the aircraft used as targets in the field firings, fires are assessed by experts from the Navy and Air Force as to whether or not the damage is "A" damage. The assessments of damage to aircraft on the ground are intended to be estimates of the impairment of performance that would have occurred had the aircraft been in flight. For new aircraft, not fired upon, the probability of a kill when a fire occurs is estimated by the Air Force assessors. This estimate depends on the location of the tank in the plane and the probable severity of fire for the type of ammunition or fragment under study. The probable severity of fire in turn is estimated from the field trials which determine the average amount of leakage obtained by the test ammunition.

RESULTS OF FIRINGS AGAINST FUEL CELLS IN AIRCRAFT WINGS

Incendiary Bullet Impacts. The results of field trails against the P-38 conducted up to 1 January 1948 are presented for various types of incendiary bullets in Table I. The listing of the firing records describing damage in detail appears in Appendix D. Partial results are included for the current series of 2000 yard firings of Cal. 0.60 and 20mm ammunition. It is expected that the final results will be incorporated in Table I and presented in a future report, as will the final results of the current series of functioning tests against various thicknesses of Alclad at a number of obliquities and over a wide range of striking velocities.

The various conditional probabilities appearing in the formula for P_{A_F}, are defined as ratios in Table I to indicate their origin. Thus (P F/fcn, CP) is the ratio $\frac{F_{ss}}{CP_{ss}}$ for single-shot fire, and $\frac{F_c}{CP_c}$ for for compound fires. Similarly,

$$(P\ A/F) = \bar{A}_{F_{ss}} \text{ or } \bar{A}_{F_c}$$

for single shot or compound fires, respectively and

$$(P\ CP/H) = \frac{CP_{ss}}{H_{ss}} \text{ or } \frac{CP_c}{H_c} \quad .$$

(P fcn/CP) may also be computed from Table I as the ratio of "hits excluding duds" to "hits including duds". In Table I, the line of fire is designated by both the angle θ, which is the angle in a horizontal plane between the line of fire and the longitudinal axis of the fuselage and the angle $\emptyset$, which is the angle that the plane of the wings makes with the horizontal. The plane of the wings is defined as the plane passing through the leading and trailing edges. "Leading edge up" is referred to as a positive angle for $\emptyset$ and "leading edge down" as negative. It is not necessary to distinguish between positive and negative values of θ because of the symmetry in the horizontal plane about the longitudinal axis for the cases considered.

The results of firings against other aircraft types have been tabulated in BRLM 462. Graphs of these results appear in the present report as well. The description of the fuel tank installations for the various aircraft targets also appear in BRLM 462.

No attempt at thorough explanation of observed differences will be made at this time. It is hoped to present a complete statistical analysis at the conclusion of the firings. The observed results are plotted in Figures 2 through 25. Since some firings are still in progress, confidence intervals have not been shown on the figures. However, the sample sizes are indicated at each observational point and so such intervals may be readily computed if desired.

The P-38 was fired upon from two directions, (1) from the front, the line of fire making an azimuthal angle $\theta = 20^\circ$ in the horizontal plane with the longitudinal axis of the plane and a vertical angle $\emptyset = 13^\circ$ with the plane of the wings, impacting the lower skin, and (2) from the rear, with $\Theta = 20^{\circ}$ again and $\emptyset = -13^{\circ}$; that is making an angle of 13° with the plane of the wings and impacting the upper skin. These two directions were also employed in the firings against fuel cells installed in other types of aircraft. Hereinafter these two directions are designated simply "front below" and "rear above".

Figure 2 presents the fraction of those rounds impacting on P-38 wings, which functioned as a result of impact. Functioning was recorded by proof directors and assessors both from observation of visual flash and by examination of impact area for characteristic blackening and charring effects.

For functioning, one may combine impacts, with no regard as to whether tanks were filled with gasoline or kerosene and whether or not there was previous leakage in the wing. Since no significant differences were obtained in functioning for firing from the front as compared to firing from the rear, the results for the two directions were combined in Figure 2. Upon the completion of the current functioning tests described in a later section it will be possible to study the relation between functioning on simple sheets of alclad and functioning on the more complex wing structure. It is possible to alter the sensitivity of small arms incendiary bullets (which function by nose friction effect) and thus effectively increase the probability of proper functioning at the lower striking velocities. The sensitivity may be adjusted to give functioning at a closer location on a specific target. The Heinkel type target has been used for this purpose in the past.[1] A major problem is the definition and description of the target to be encountered.

The same problem exists in part for fusing of high explosive shell. The M75 fuze assembled in the 20mm, HEI, M97 has shown erratic functioning in most phases of the firings against aircraft targets. This is a relatively insensitive fuze whose functioning depends markedly on the thickness of the target material. The requirements for consistent and proper functioning of a fuze for this size and type of high explosive shell will be demonstrated in a following section of this report.

Figure 3 depicts the observed probability of functioning for impacts on all target planes combined.

Figures 4 and 5 show the observed probabilities that projectiles which impact on the projected area of a P-38 fuel tank will perforate the tank wall. A projectile may impact the projected area and not perforate a tank due to ricochet or insufficient remaining velocity.

Figures 6 and 7 present the combined results for firings against the P-38, P-59, A-35 and B-25. The latter three aircraft were employed as fuel tank targets at the one range of 500 yards. Cell perforation does not depend on the type of fuel or on the presence of leakage from previous hits. Consequently the gasoline and kerosene filled tanks and the single shot and compound hits were combined for Figures 4 through 7.

Figures 8 and 9 show the observed single-shot probability of obtaining fires for gasoline and for kerosene filled tanks. For these figures, all functioning perforations were considered for projectiles impacting on previously undamaged cells and in areas in which there was no fuel leakage due to any reason. The data for front below and rear above were combined. Figures 10 and 11 present the observed compound probabilities for obtaining fires when perforations are obtained through previously damaged and leaking cells (or cells in a region in which fuel has been observed outside the tanks for any reason).

Figures 12 through 15 are a similar series which include non-functioning hits in the number of

[1] Record of Army Ordnance Research and Development, Volume 2, Small Arms and Small Arms Ammunition, Book 2, Small Arms Ammunition (C).

perforations. Figures 16 through 19 also include non-functioning hits in the number of cell perforations, but the data from firings at a range of 500 yards have now been augmented by inclusion of firings against the P-59, A-35 and B-25.

It is interesting at this time to present a previously unpublished chart, Figure 19a, prepared by Colonel R. R. Studler, Ordnance Department, depicting the probability of obtaining ignition on a Heinkel replica target. A description of the Heinkel targets and the firings against them is given in the Ordnance Department manual on Small Arms Ammunition.[1] A typical Heinkel replica arrangement is shown in Figure 19b.

The difference which will be noted between the values given in this chart and the results reported in the present study may be attributed to the difference between the Heinkel replica target and the P-38 structure and also to the difference in conditions of the experiment. For example, a slipstream was directed over the P-38 target but not over the Heinkel.

Figures 20 through 23 illustrate the average single-shot "A" and "B" assessments given by the Air Force assessors to the observed fires. These charts are highly erratic in the sense that the graphs are not monotonically increasing with increasing striking velocity. The sample sizes for these figures are the smallest of all since not very many hits resulted in fires. These figures are not the result of observed fact only, such as those described previously, but include assessor opinion. It should be remembered that the stream of air provided over the target wings by the slave engine is extremely effective in extinguishing fires with external sources. The air stream over the target wings usually was from 80 to 100 mph and often after the slave engine was shut off a large fire would immediately flare where previously only smoke was seen. Tests conducted by Wright Field indicate that if a fire is not blown out by the time a plane is traveling at about 110 mph then it would not be blown out at any speed and probably has an internal source, protected from the air stream.[2]

Although assessments are made as though the aircraft were in actual flight there is obviously much room for difference of opinion. An attempt has been made to determine the average difference of assessments of the same damage by having more than one assessor give an independent assessment. These results have not yet been analyzed. It is noted, however, that much damage is either obviously non-lethal or obviously lethal. Such damage receives 0A or 100A assessments and constitutes over 90% of the observed data. The "B" damage assessments are more reliable than the "A" assessments since it is much easier to determine whether the damage is lethal within 2 hours than within 5 minutes. In this regard it is interesting to note that many reports of battle damage sustained in the last war indicate that few aircraft that caught fire returned to base. The (P A/F) factor in the calculation of the probability of "A" damage due to fuel sustained by any target aircraft under study will usually have a different value than is indicated in the Figures 20 - 23 since the seriousness of fire will depend on the location of the tank and on the availability and efficiency of fire extinguishing equipment.

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[1] Record of Army Ordnance Research and Development, Volume 2, Small Arms and Small Arms Ammunition, Book 2, Small Arms Ammunition (C).

[2] TSEPP-144-1698, "Summary of Data on Fires and Explosions in Aircraft Fuel Tanks," 13 Sept. 1946, Appendix I, page 9.

The observed probabilities of obtaining self-sealing as a function of striking velocity are indicated in Figures 24 and 25 for gasoline and kerosene. It should be noted that both the fracture of the nose and the tumbling of incendiary projectiles influence the self-sealing property of tanks. Most American self-sealing tanks have been designed to prevent "defeat" by Cal. 0.50 AP ammunition. That is to say, they are intended to effectively seal a specified number of penetrations by this caliber. So long as the penetration of the tank occurs by puncture, as from normal impact by a streamlined bullet, these tanks may seal Cal. 0.60 and often even 20mm projectiles. However, so-called "plugging" of the tank, where a piece of the tank is actually removed, will usually result in its defeat. An incendiary bullet may assist this "plugging" action by burning of rubber and by virtue of the break-up of the nose, resulting in a penetration by a jagged blunt nose. Thus, too, jagged irregular fragments of the same weight as the Cal. 0.50 bullet (about 700 grains) will also result in plugging and consequent defeat of the self-sealing action. The method whereby the nose of an incendiary bullet breaks is strikingly exhibited by a series of radiographic studies conducted at Frankford Arsenal.[1, 2]

In this report results have been expressed in terms of striking velocity rather than ground range. Figure 25a shows the relationship between striking velocity and ground range when the bullets are fired from a stationary gun.

Empirical Formulae. The usefulness of the experimental data presented in this report depends, in part, upon the extent to which it can be extrapolated to designs of ammunition which have not been fired. Empirical formulae fitting the experimental data are an aid to such extrapolation.

An empirical formula has been proposed by Mr. H. K. Weiss to fit the information presented in Figure 8, the fires per cell penetration, on P-38 gasoline-filled fuel cells. It is

$$p_f = 1 - 2.3 \exp -1.1\, v_s w_p^{1/2}\, w_f^{1/4}$$

where

p_f = fires per cell penetration = F_{ss}/CP_{ss}

v_s = striking velocity in units of 1000 ft/sec

w_p = projectile weight in units of 1000 grains

w_f = filler weight in units of 100 grains

As a typical example of the use of the formula, consider the T36E2 Cal. 0.60 round striking at 2100 ft./sec. The projectile weight is 1150 grains and the filler weight is 92 grains. The formula yields a value of p_f

$$p_f = 1 - 2.3 \exp (-1.1)\,(2.1)\,(1.15)^{1/2}\,(.92)^{1/4}$$
$$= 0.80$$

The value from Figure 8 is 0.78, which however, is a closer match than is obtained for some of the other points. Figure 26b shows p_f computed from the formula for the five incendiary and armor piercing rounds of Figure 8. Also shown in Figure 26b are the experimental points given in Figure 8.

[1] FA T2161, "X-Ray Pictures of Current Production Caliber .30 M1 Incendiary Bullets During Performance Tests", E. R. Thilo.

[2] FA R-321 "X-Ray Pictures of Current Production Caliber 0.50 M1 Incendiary During Performance Tests, First Report", E. R. Thilo, May 1943.

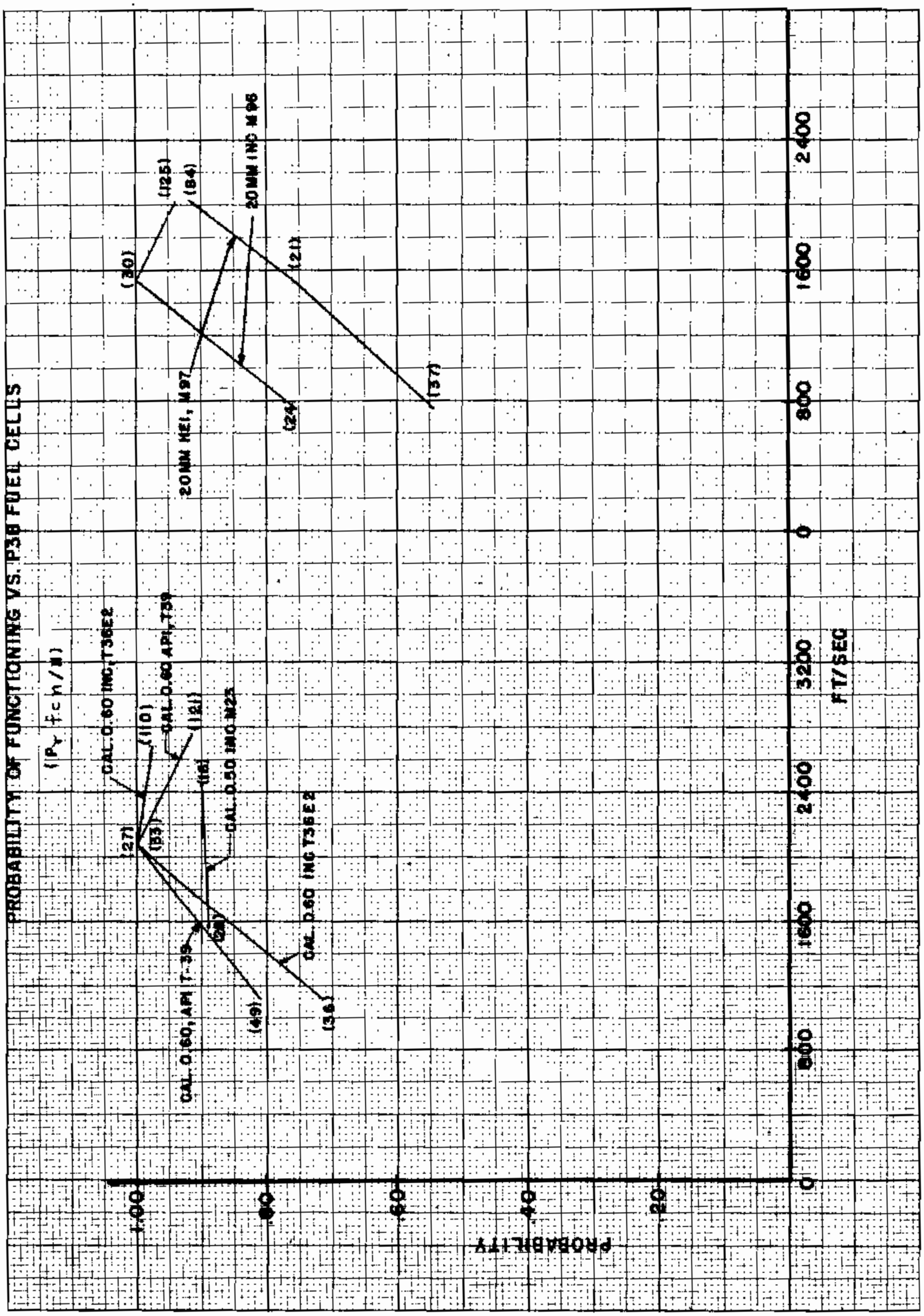

PROBABILITY OF FUNCTIONING VS. P38 FUEL CELLS
CAL. 0.60 INC. T36E2
CAL. 0.60 API, T39
CAL. 0.50 INC M23
CAL. 0.60 INC T36E2
CAL. 0.60, API T-39
20MM INC M96
20MM HEI, M97
(110)
(121)
(16)
(27)
(53)
(49)
(36)
(30)
(125)
(84)
(21)
(37)
(24)
1.00
.80
.60
.40
.20
0
800
1600
2400
3200
FT/SEC
PROBABILITY

FIG. 2

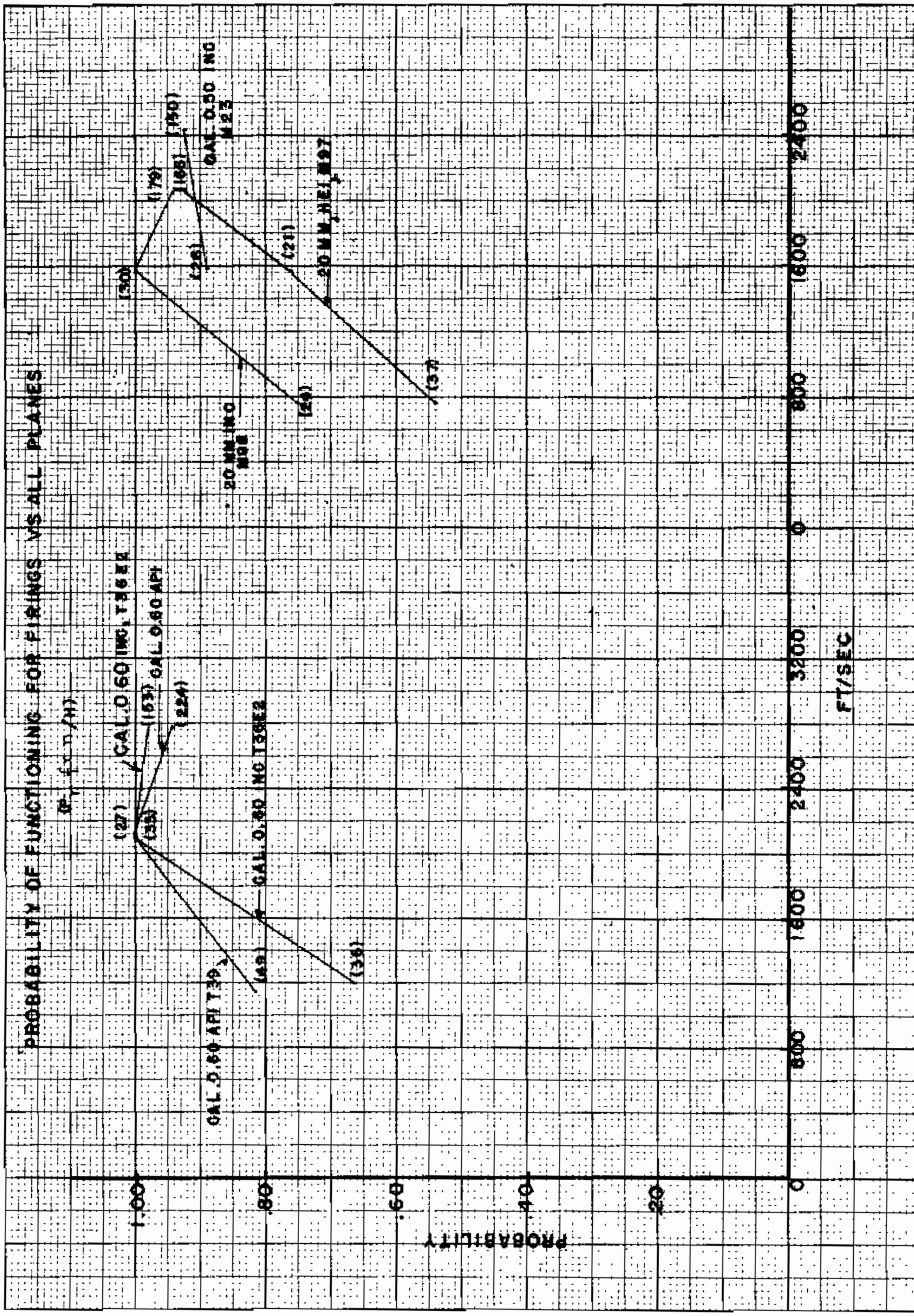

PROBABILITY OF FUNCTIONING FOR FIRINGS VS ALL PLANES
CAL. 0.60 INC. T36E2
CAL. 0.60 API
CAL. 0.60 API T39
CAL. 0.60 INC T36E2
20 MM INC M96
20 MM HEI M97
CAL. 0.50 INC M23
PROBABILITY
FT/SEC

FIG. 3

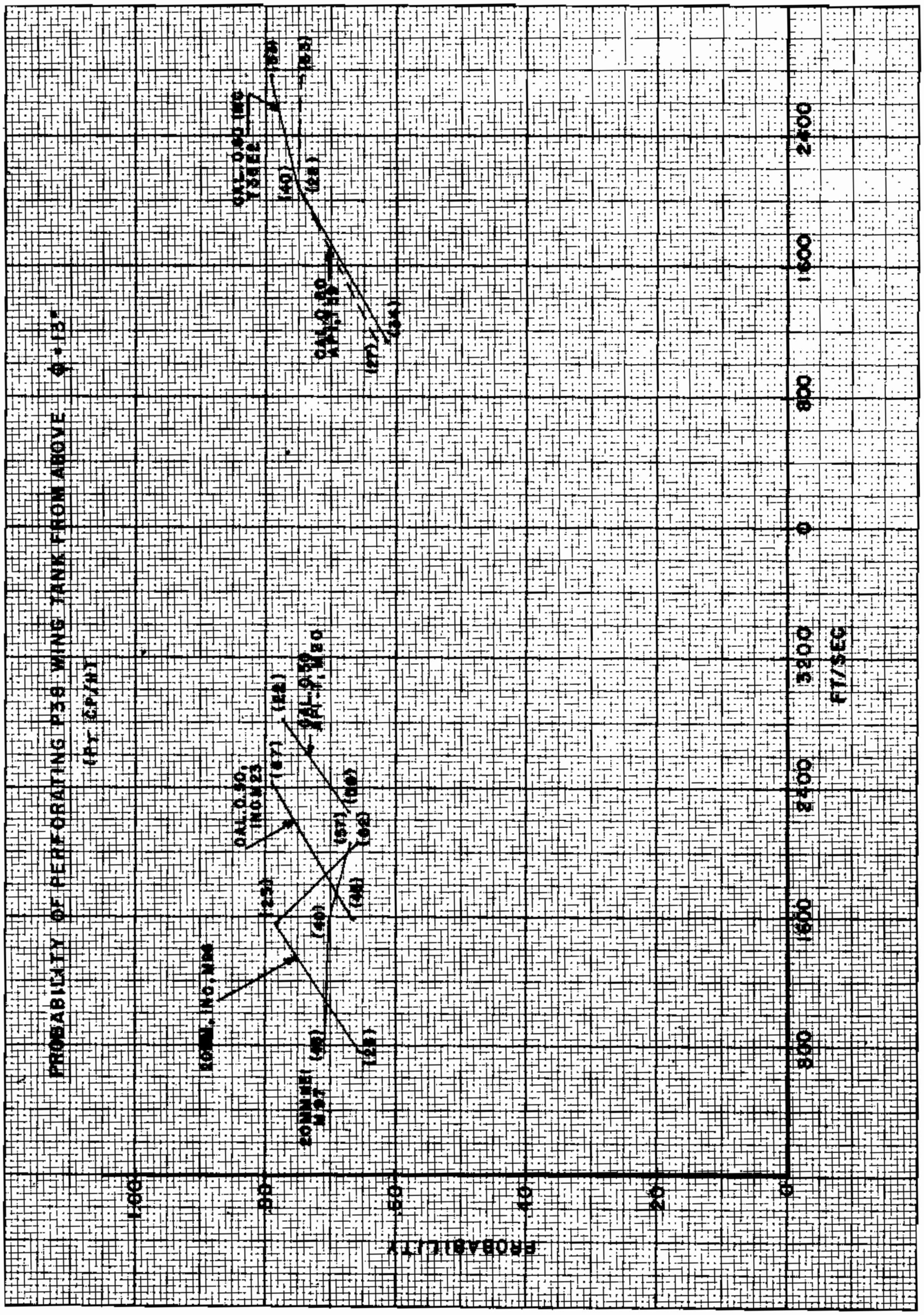
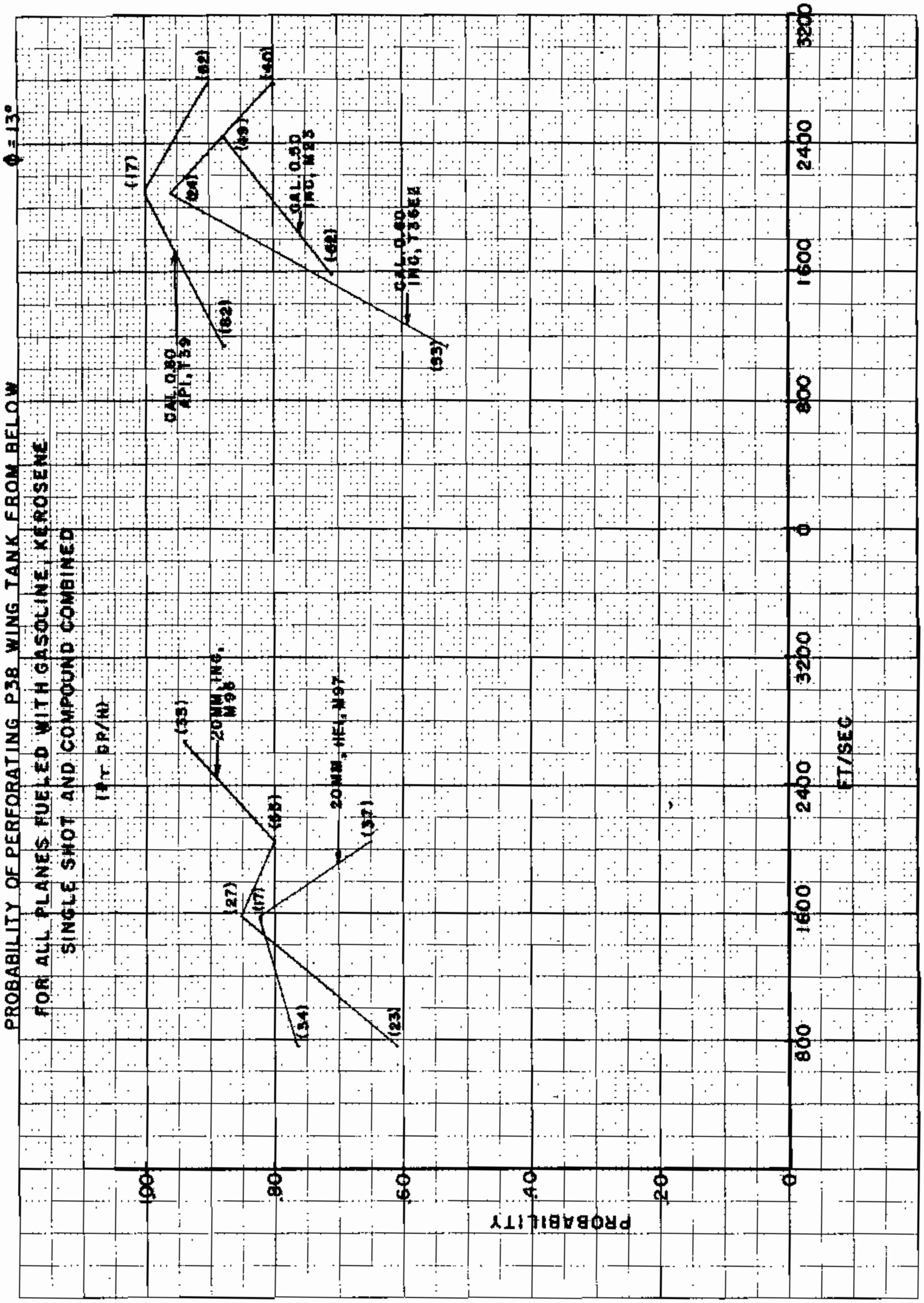

PROBABILITY OF PERFORATING P38 WING TANK FROM ABOVE
FT/SEC
PROBABILITY

FIG. 4



PROBABILITY OF PERFORATING P38 WING TANK FROM BELOW
FOR ALL PLANES FUELED WITH GASOLINE, KEROSENE
SINGLE SHOT AND COMPOUND COMBINED
Φ = 13°
CAL 0.50 API, T59
CAL 0.50 INC, M23
CAL 0.60 INC, T36E4
20MM, INC, M96
20MM, HEI, M97
PROBABILITY
FT/SEC

FIG. 5

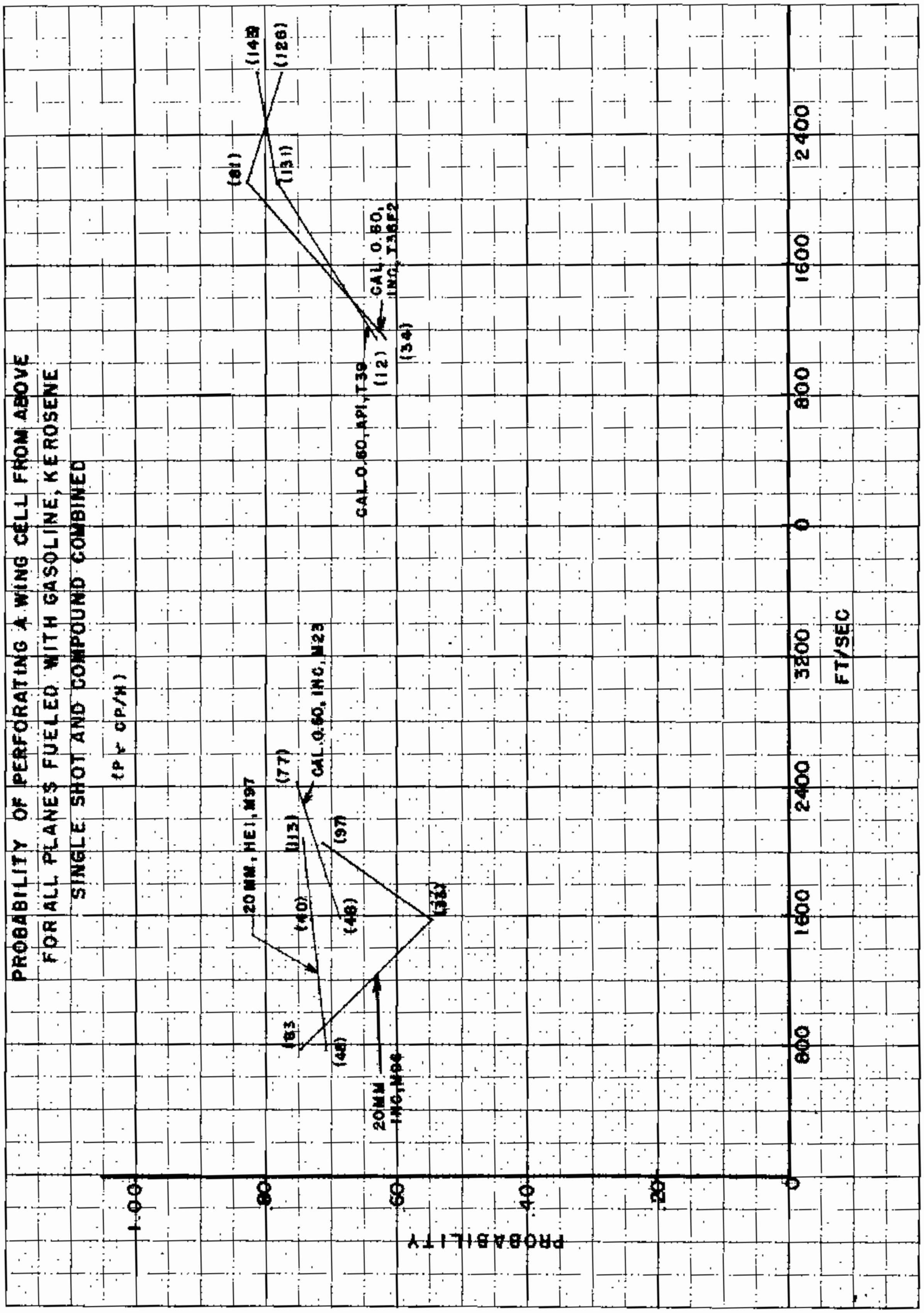
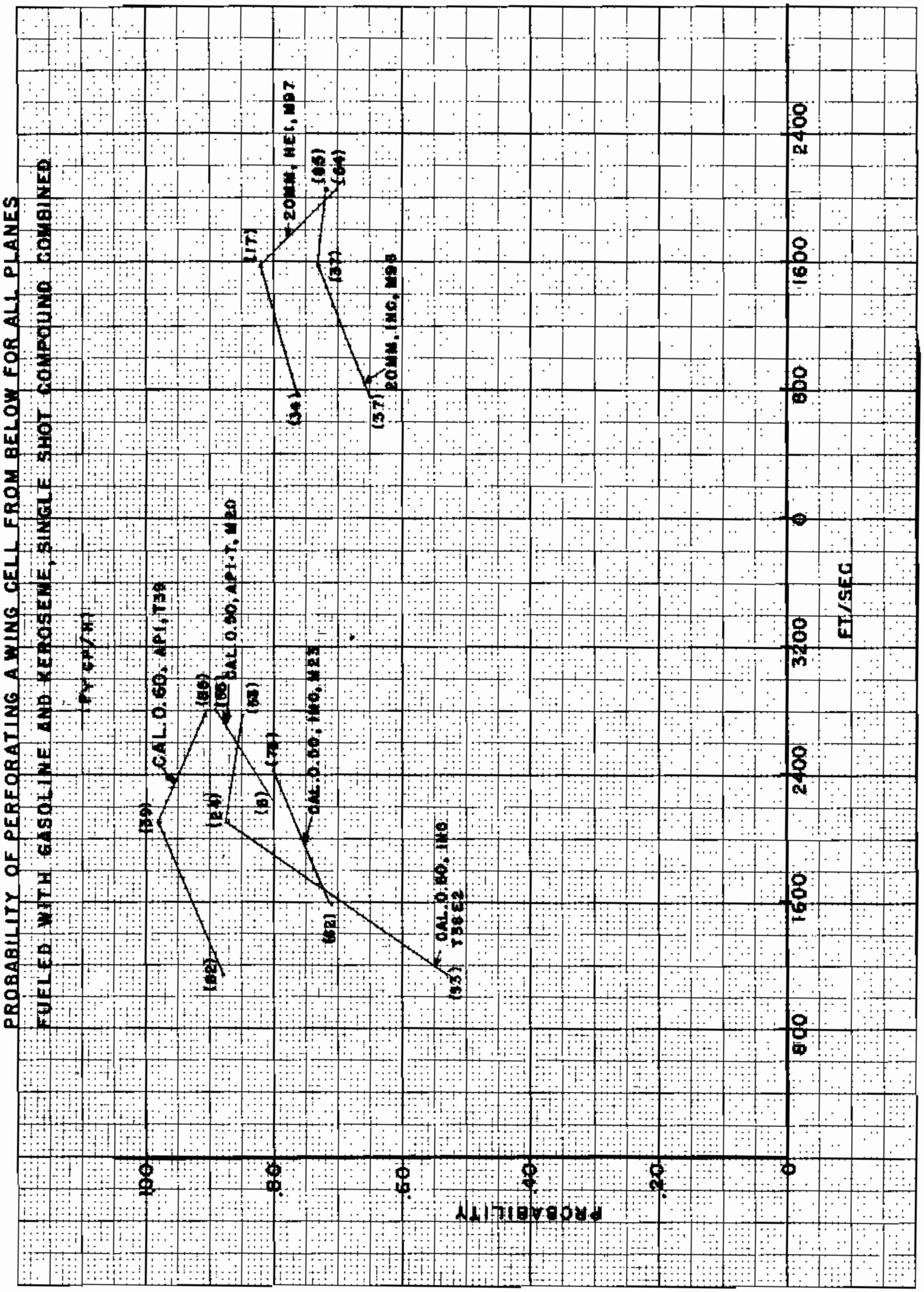

PROBABILITY OF PERFORATING A WING CELL FROM ABOVE
FOR ALL PLANES FUELED WITH GASOLINE, KEROSENE
SINGLE SHOT AND COMPOUND COMBINED
(P = CP/H)
20 MM, HEI, M97
CAL.0.50, INC, M23
20MM
INC, M96
CAL.0.60, API, T39
CAL. 0.50,
INC, T38E2
(149)
(126)
(81)
(131)
(34)
(12)
(77)
(113)
(97)
(40)
(48)
(32)
(83)
(48)
PROBABILITY
1.00
80
60
40
20
0
800
1600
2400
3200
0
800
1600
2400
FT/SEC

FIG. 6



PROBABILITY OF PERFORATING A WING CELL FROM BELOW FOR ALL PLANES
FUELED WITH GASOLINE AND KEROSENE, SINGLE SHOT COMPOUND COMBINED
CAL.0.60, API, T39
CAL.0.50, API-T, M20
CAL.0.50, INC, M23
CAL.0.60, INC T38 E2
20MM. HEI, M97
20MM. INC, M96
PROBABILITY
FT/SEC

FIG.7

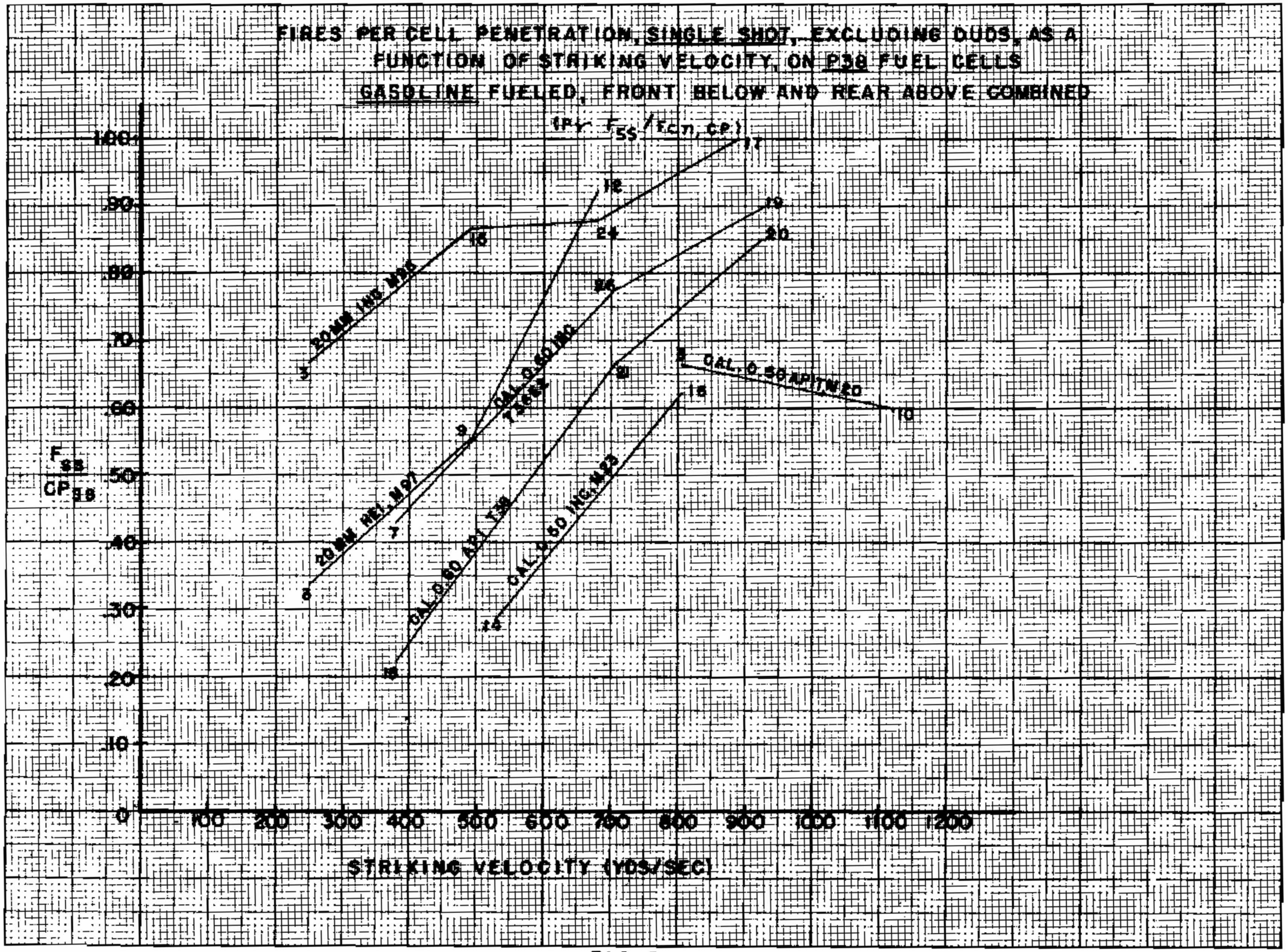

FIRES PER CELL PENETRATION, SINGLE SHOT, EXCLUDING DUDS, AS A
FUNCTION OF STRIKING VELOCITY, ON P38 FUEL CELLS
GASOLINE FUELED, FRONT BELOW AND REAR ABOVE COMBINED
20MM INC M96
20MM HEI, M97
CAL. 0.60 INC T26E2
CAL. 0.60 API T39
CAL. 0.50 INC. M23
CAL. 0.50 API T M20
$\frac{F_{SS}}{CP_{SS}}$
STRIKING VELOCITY (YDS/SEC)

FIG. 8

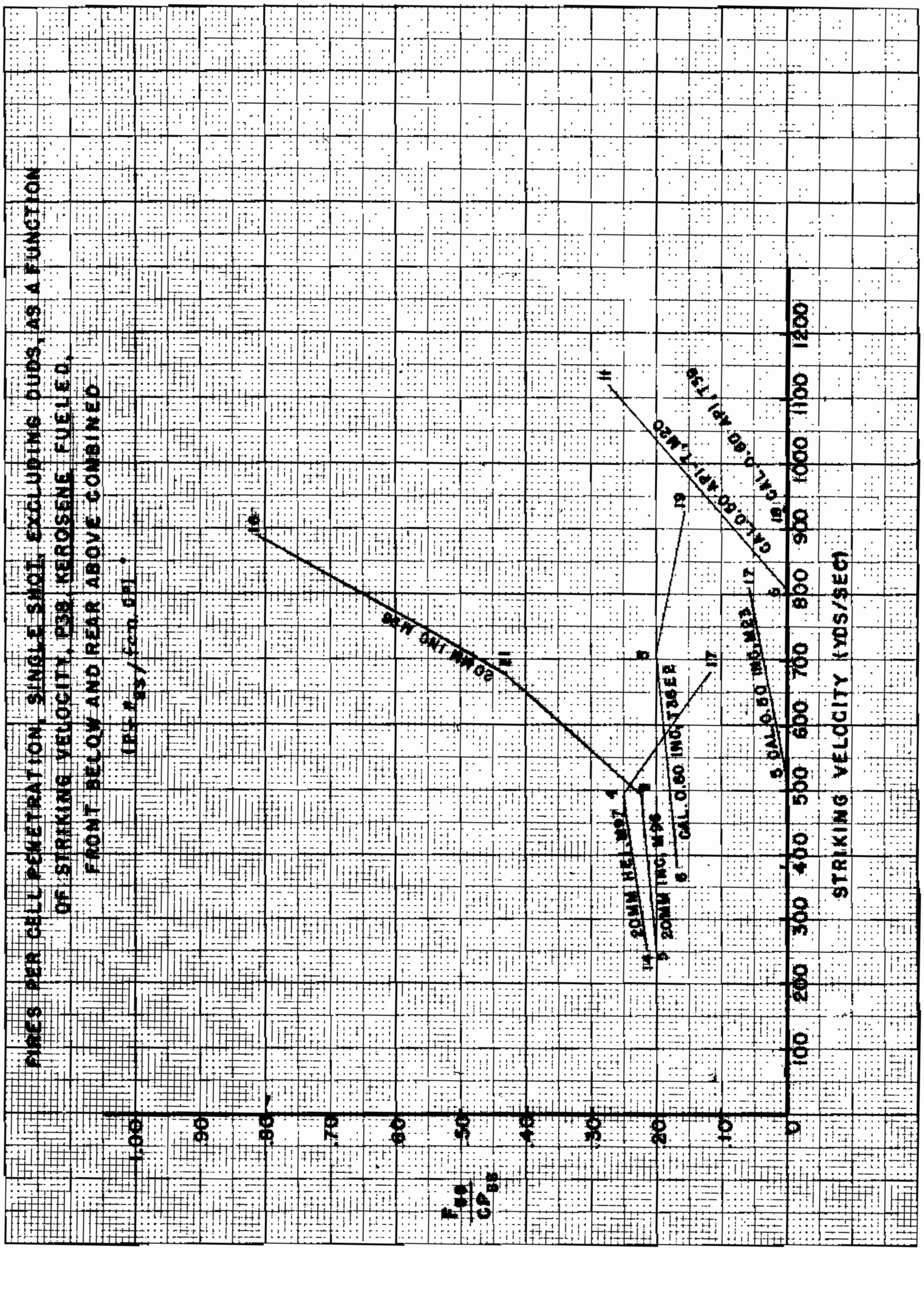

FIRES PER CELL PENETRATION, SINGLE SHOT, EXCLUDING DUDS, AS A FUNCTION
OF STRIKING VELOCITY, P38 KEROSENE FUELED,
FRONT BELOW AND REAR ABOVE COMBINED
20MM INC M96
20MM H.E. M97
20MM INC M96
CAL. 0.60 INC T36E2
CAL. 0.50 INC M23
CAL. 0.60 API T39
STRIKING VELOCITY (YDS/SEC)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
0
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00

FIG.9

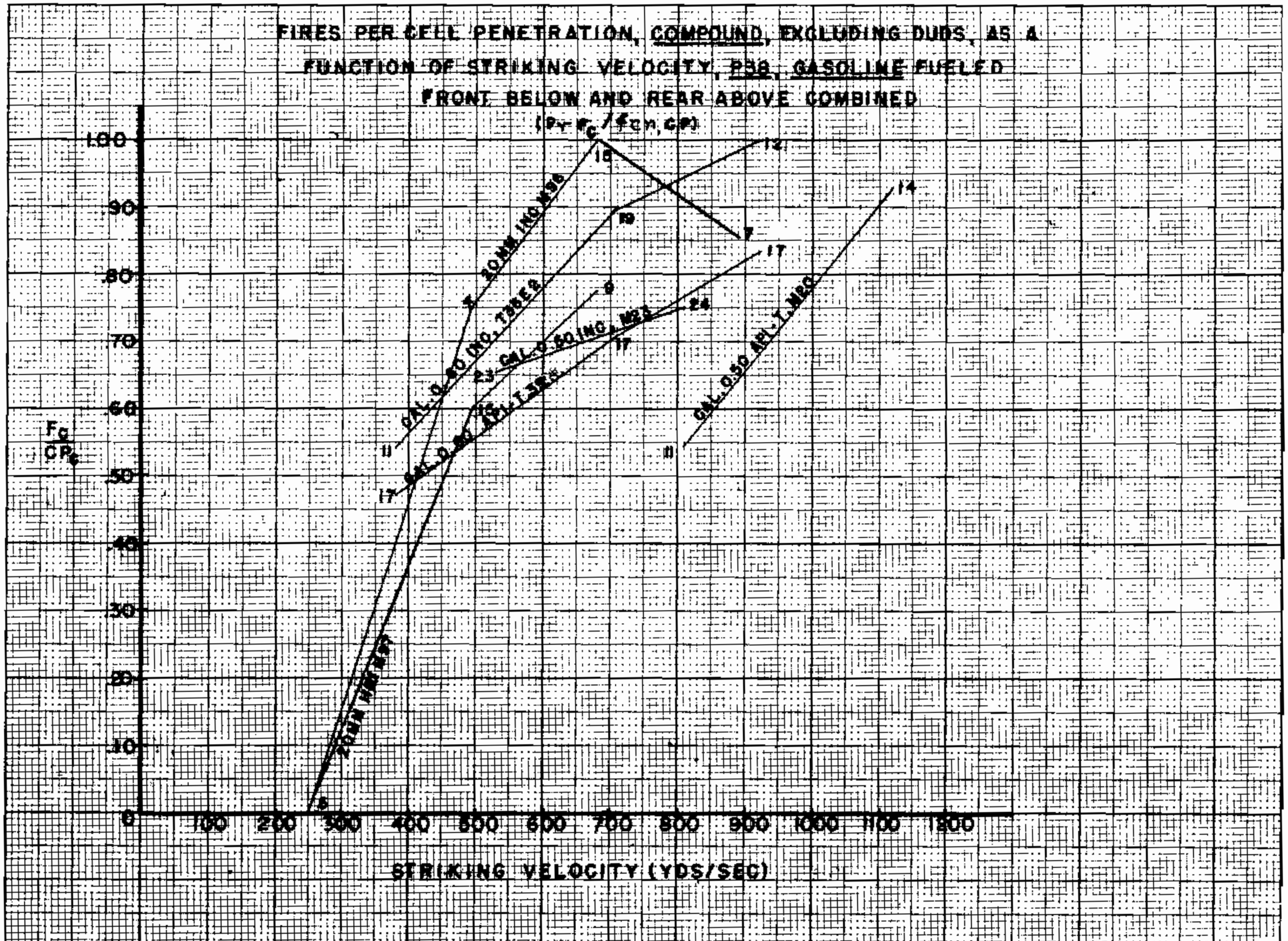

FIRES PER CELL PENETRATION, COMPOUND, EXCLUDING DUDS, AS A
FUNCTION OF STRIKING VELOCITY, P38, GASOLINE FUELED
FRONT BELOW AND REAR ABOVE COMBINED
$\frac{F_c}{CP_c}$
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
STRIKING VELOCITY (YDS/SEC)
CAL. 0.50 API-T M20

FIG.10

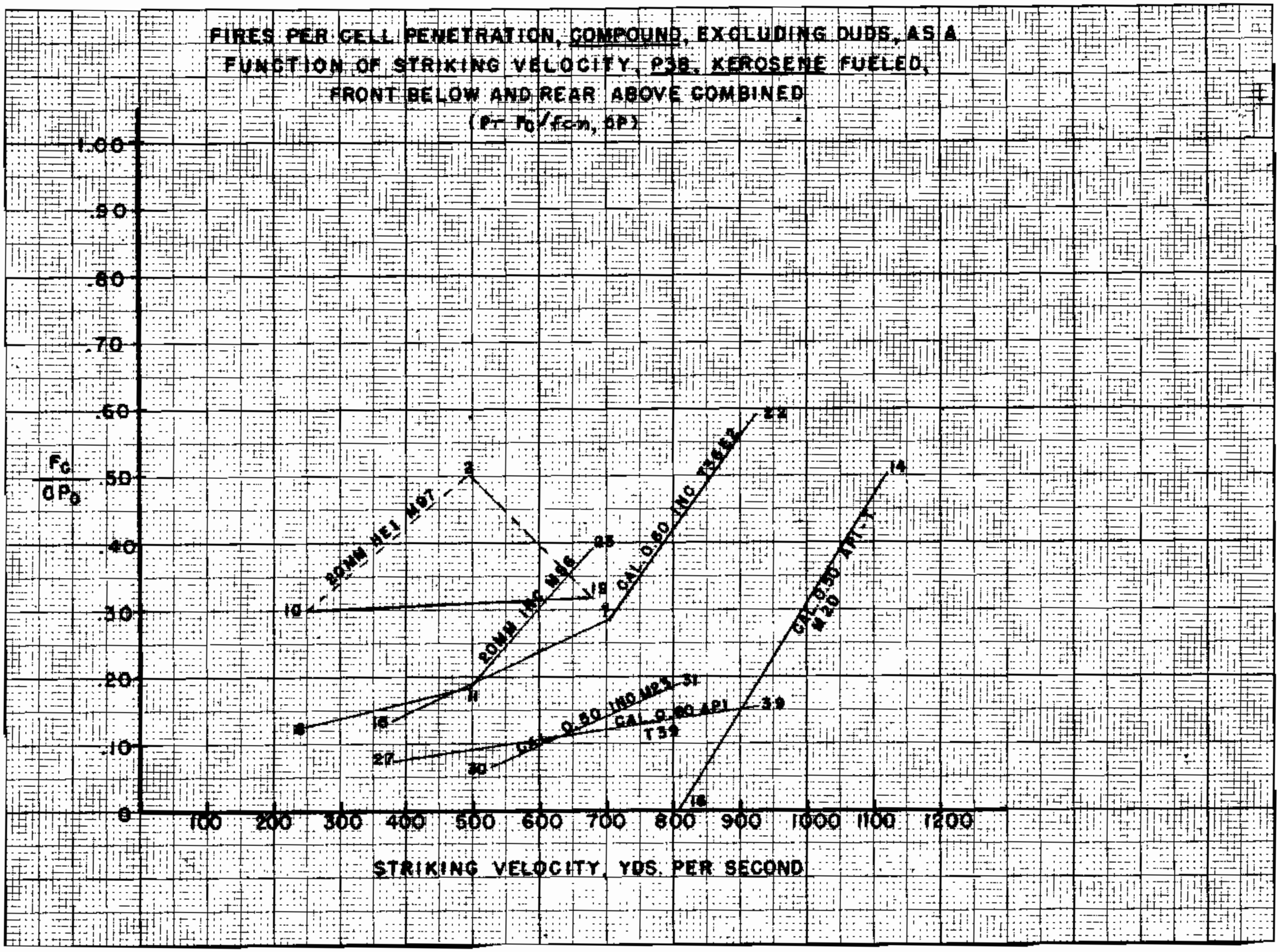

FIRES PER CELL PENETRATION, COMPOUND, EXCLUDING DUDS, AS A
FUNCTION OF STRIKING VELOCITY, P38, KEROSENE FUELED,
FRONT BELOW AND REAR ABOVE COMBINED
Fc / CPo
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
STRIKING VELOCITY, YDS. PER SECOND
20MM HEI M97
20MM INC M96
CAL 0.60 INC T36E2
CAL 0.50 API-T M20
CAL 0.50 INC M23
CAL 0.60 API T39
CAL 0.50
2
10
18
25
7
22
14
11
16
8
27
30
31
39
18

FIG. 11

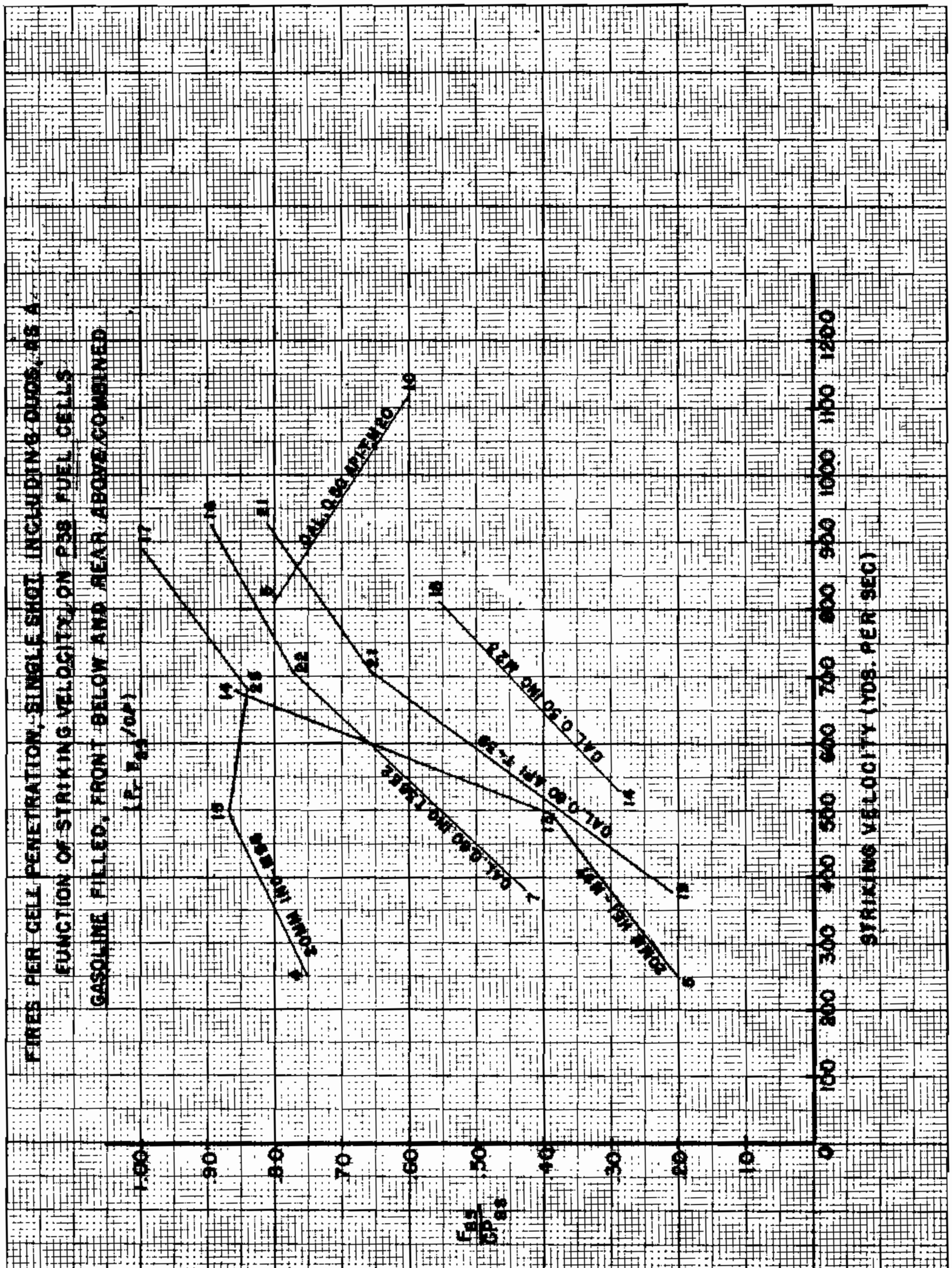
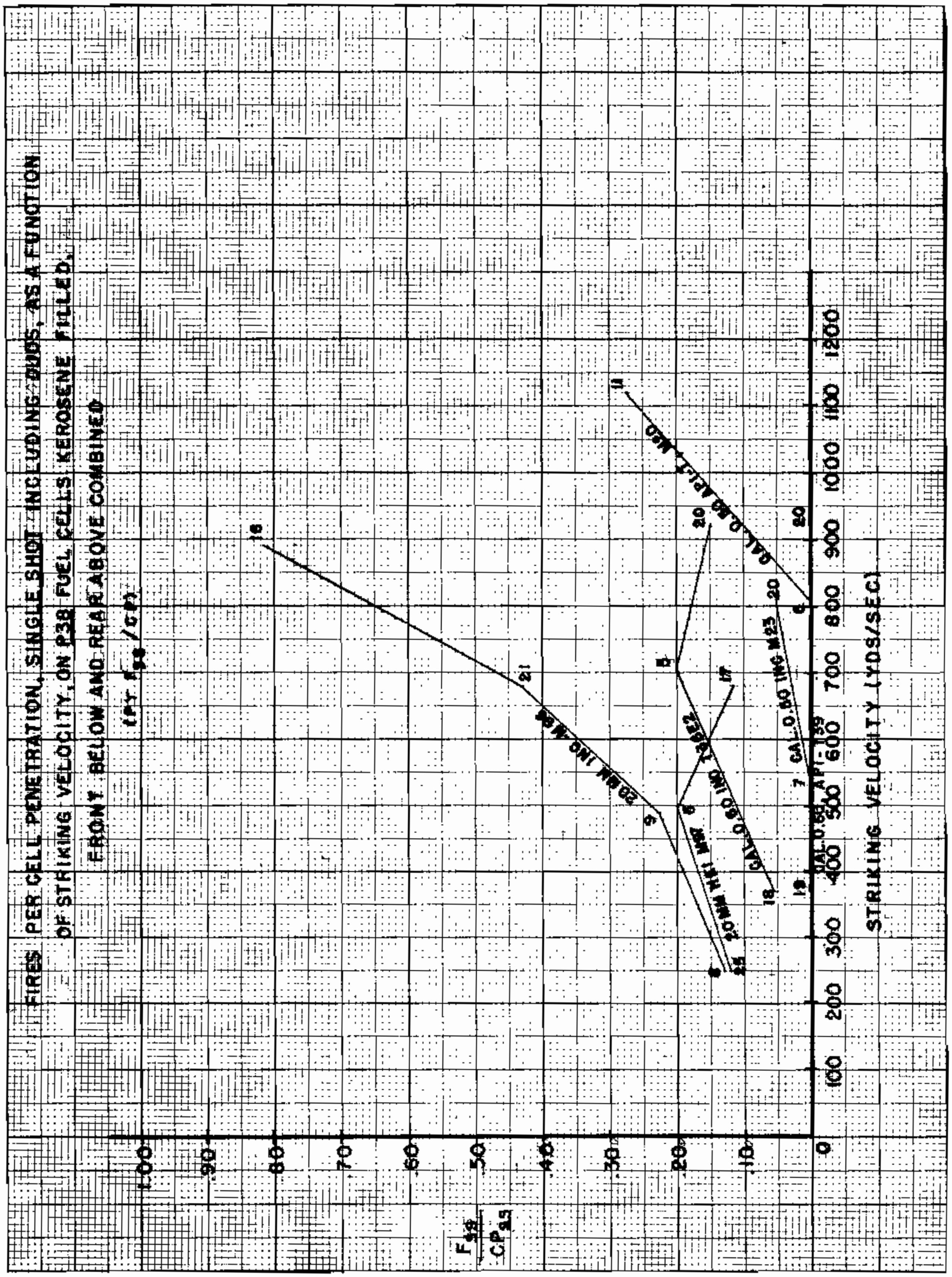

FIRES PER CELL PENETRATION, SINGLE SHOT INCLUDING DUDS, AS A
FUNCTION OF STRIKING VELOCITY, ON P38 FUEL CELLS
GASOLINE FILLED, FRONT BELOW AND REAR ABOVE COMBINED
STRIKING VELOCITY (YDS. PER SEC)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
CAL 0.50 INC M23

FIG. 12



FIRES PER CELL PENETRATION, SINGLE SHOT INCLUDING DUDS, AS A FUNCTION
OF STRIKING VELOCITY, ON P38 FUEL CELLS KEROSENE FILLED.
FRONT BELOW AND REAR ABOVE COMBINED
STRIKING VELOCITY (YDS/SEC)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
20 MM INC M96

FIG. 13

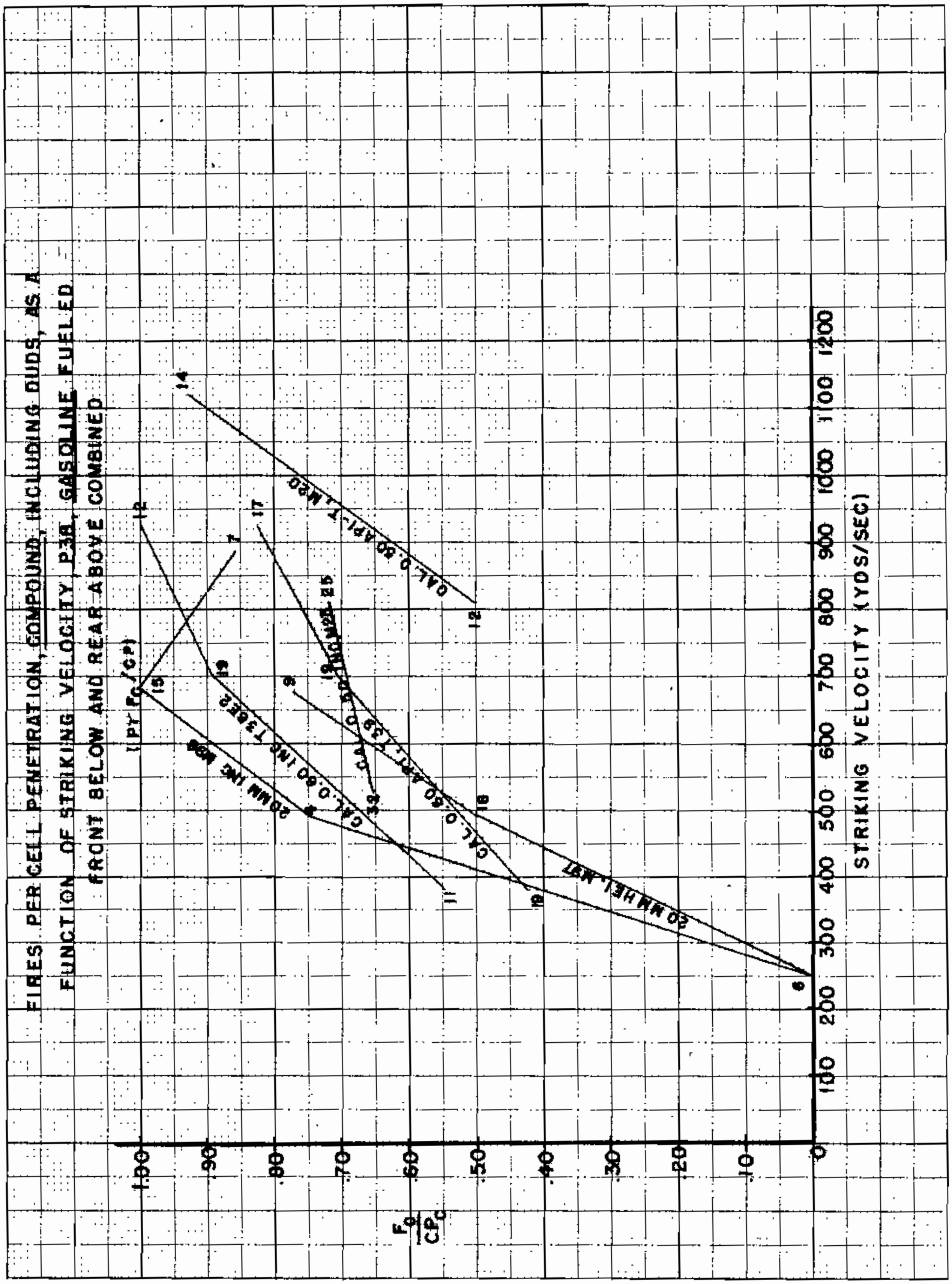

FIRES PER CELL PENETRATION, COMPOUND, INCLUDING DUDS, AS A
FUNCTION OF STRIKING VELOCITY, P38, GASOLINE FUELED
FRONT BELOW AND REAR ABOVE COMBINED
CAL. 0.50 API-T, M20
20 MM HEI, M97
20 MM INC M96
CAL. 0.60 INC T36E2
CAL. 0.60 API, T39
STRIKING VELOCITY (YDS/SEC)
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
0 .10 .20 .30 .40 .50 .60 .70 .80 .90 1.00

FIG. 14

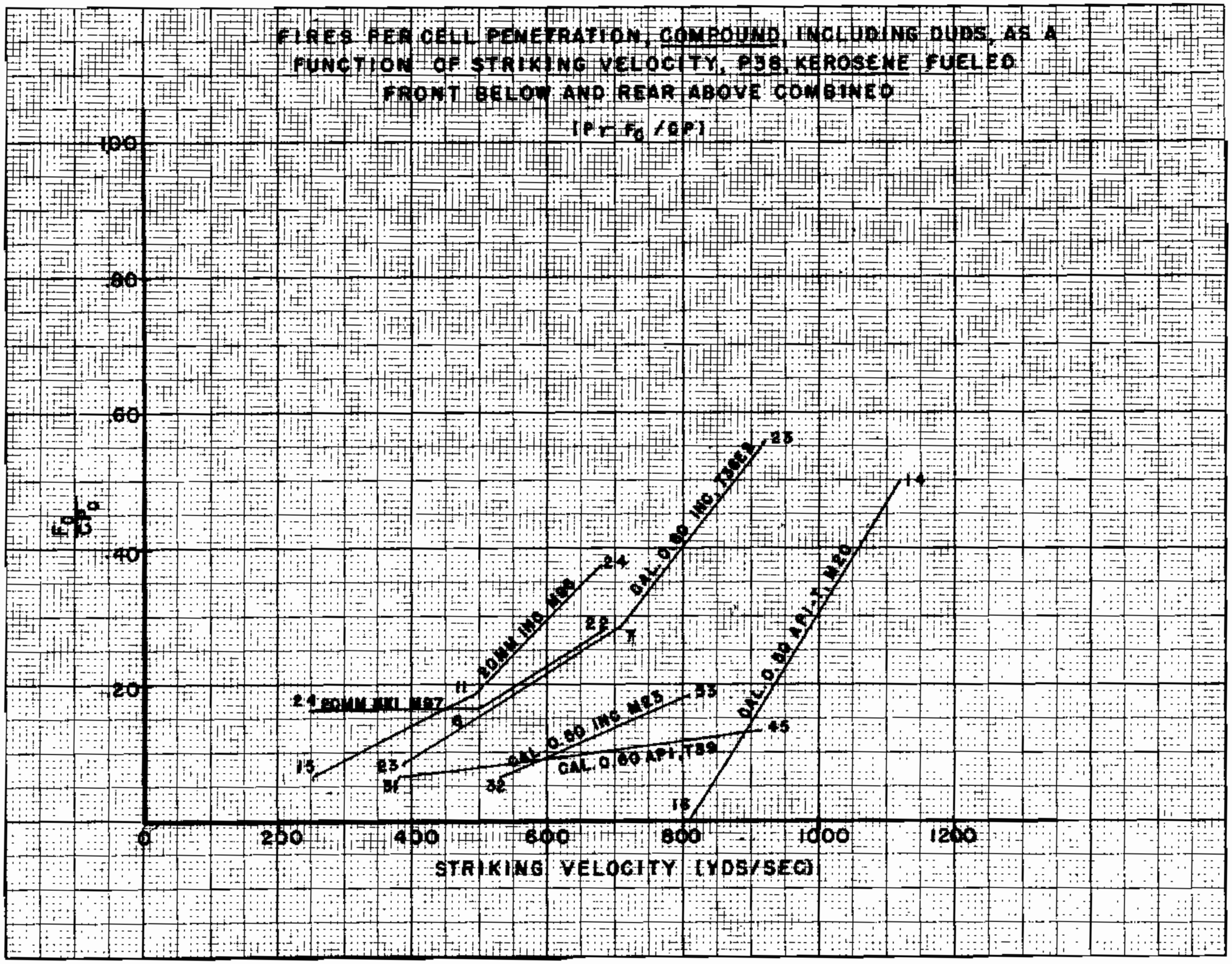

FIRES PER CELL PENETRATION, COMPOUND, INCLUDING DUDS, AS A
FUNCTION OF STRIKING VELOCITY, P38, KEROSENE FUELED
FRONT BELOW AND REAR ABOVE COMBINED
(Pr - Fc /CP)
100
80
60
40
20
0
200
400
600
800
1000
1200
STRIKING VELOCITY (YDS/SEC)
20MM HEI M97
20MM INC M96
CAL. 0.50 INC. T36E2
CAL. 0.50 INC M23
CAL. 0.50 API, T39
CAL. 0.50 API-T, M20
24
11
15
6
23
31
32
22
7
24
25
14
33
45
15

FIG. 15

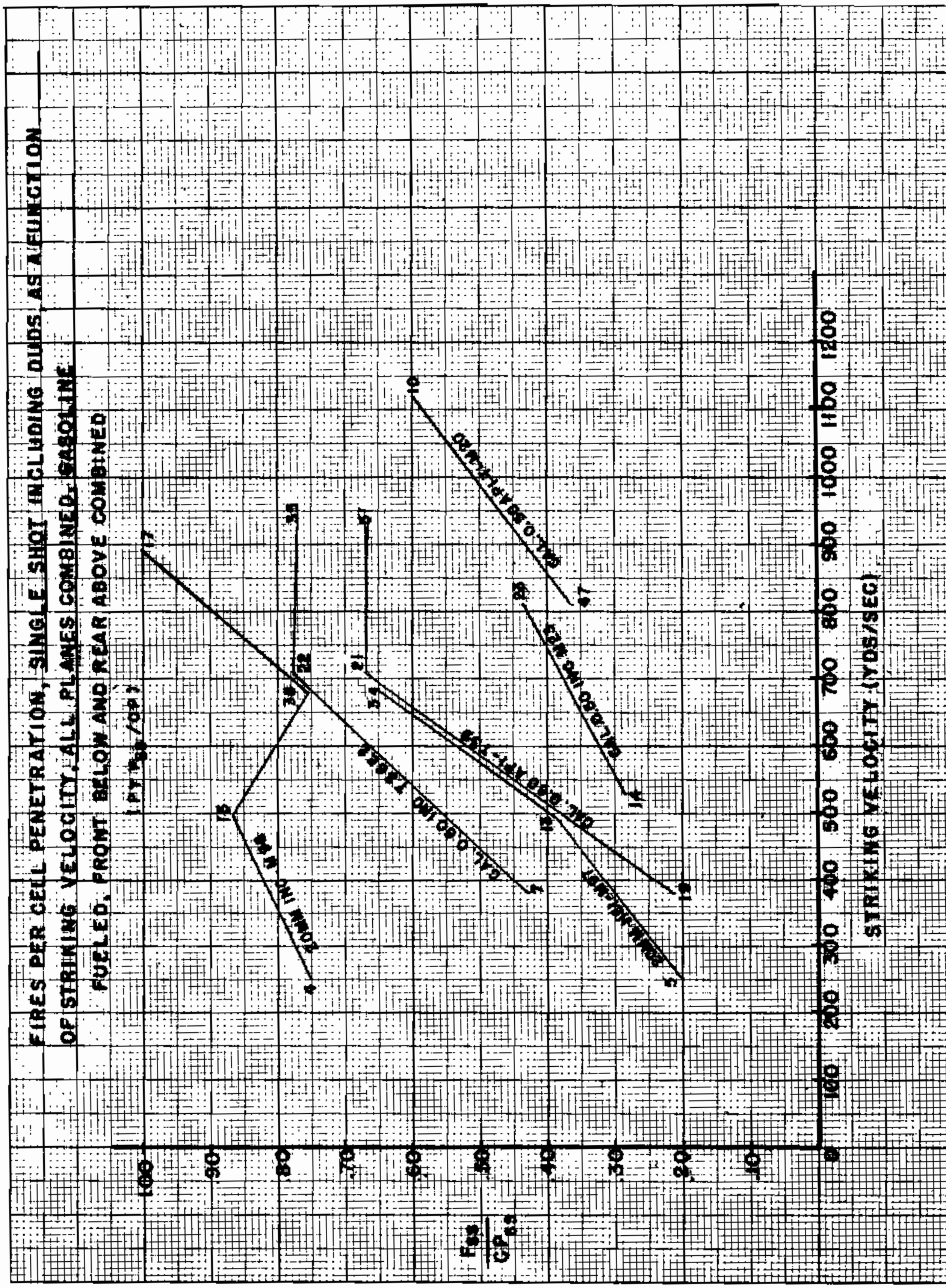

FIRES PER CELL PENETRATION, SINGLE SHOT INCLUDING DUDS AS A FUNCTION
OF STRIKING VELOCITY, ALL PLANES COMBINED, GASOLINE
FUELED, FRONT BELOW AND REAR ABOVE COMBINED
STRIKING VELOCITY (YDS/SEC)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00

FIG. 16

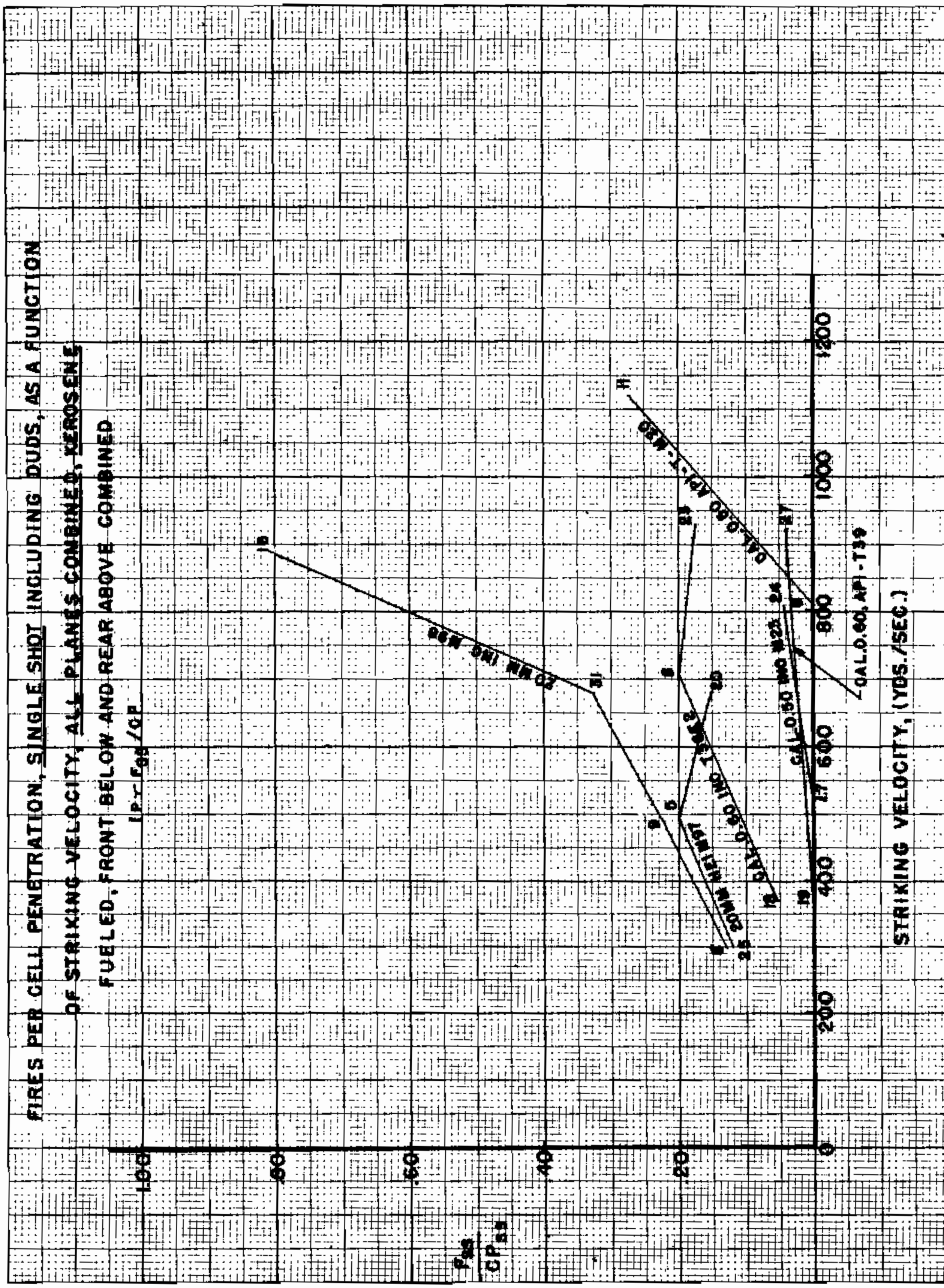

FIRES PER CELL PENETRATION, SINGLE SHOT INCLUDING DUDS, AS A FUNCTION
OF STRIKING VELOCITY, ALL PLANES COMBINED, KEROSENE
FUELED, FRONT BELOW AND REAR ABOVE COMBINED
STRIKING VELOCITY, (YDS./SEC.)
CAL.0.60, API-T39
1.00
.80
.60
.40
.20
0
200
400
600
800
1000
1200

FIG. 17

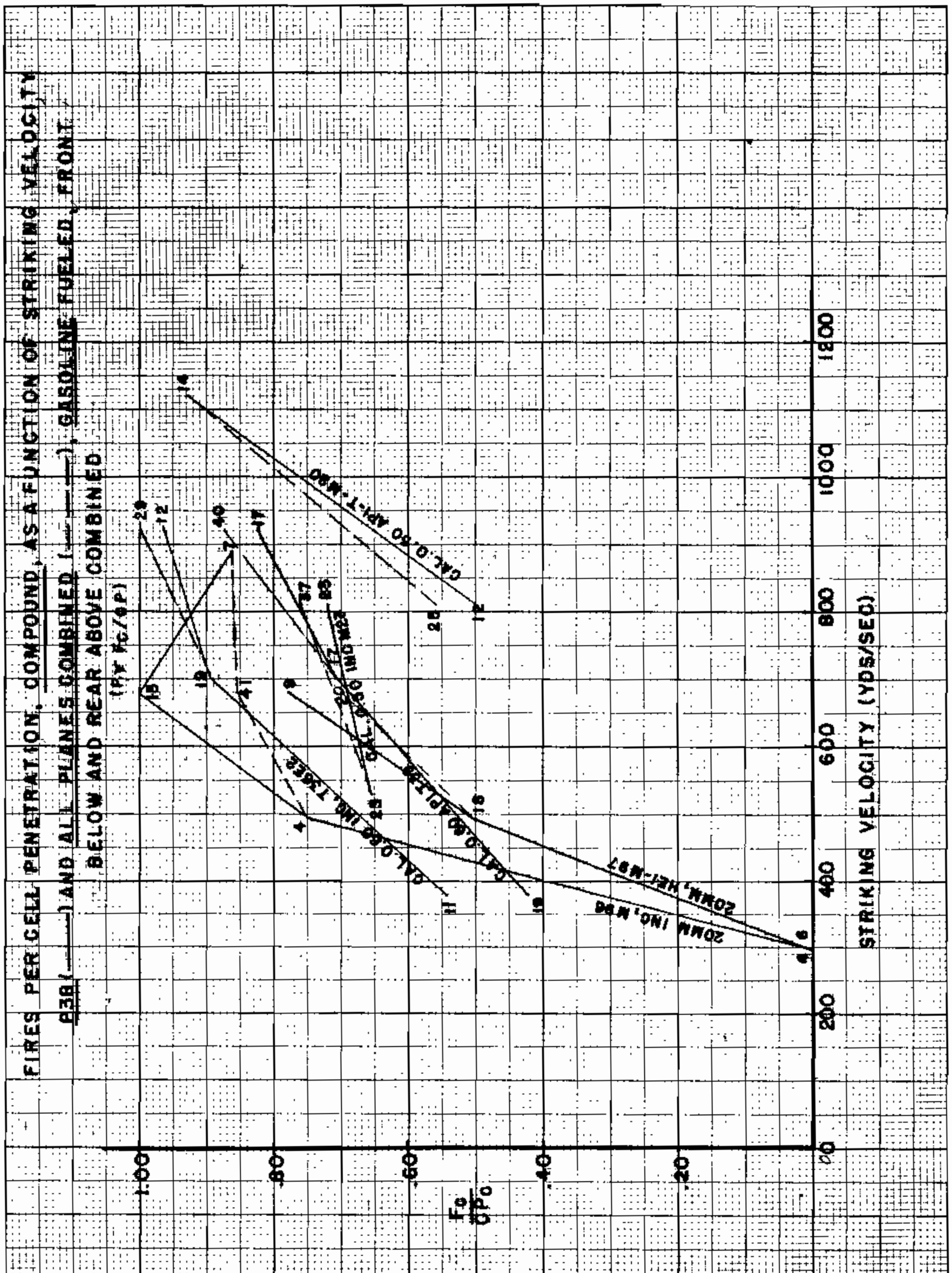

FIRES PER CELL PENETRATION, COMPOUND, AS A FUNCTION OF STRIKING VELOCITY
638 (——) AND ALL PLANES COMBINED (— — —), GASOLINE FUELED, FRONT
BELOW AND REAR ABOVE COMBINED
STRIKING VELOCITY (YDS/SEC)
20MM, HEI-M97
20MM INC, M96

FIG. 18

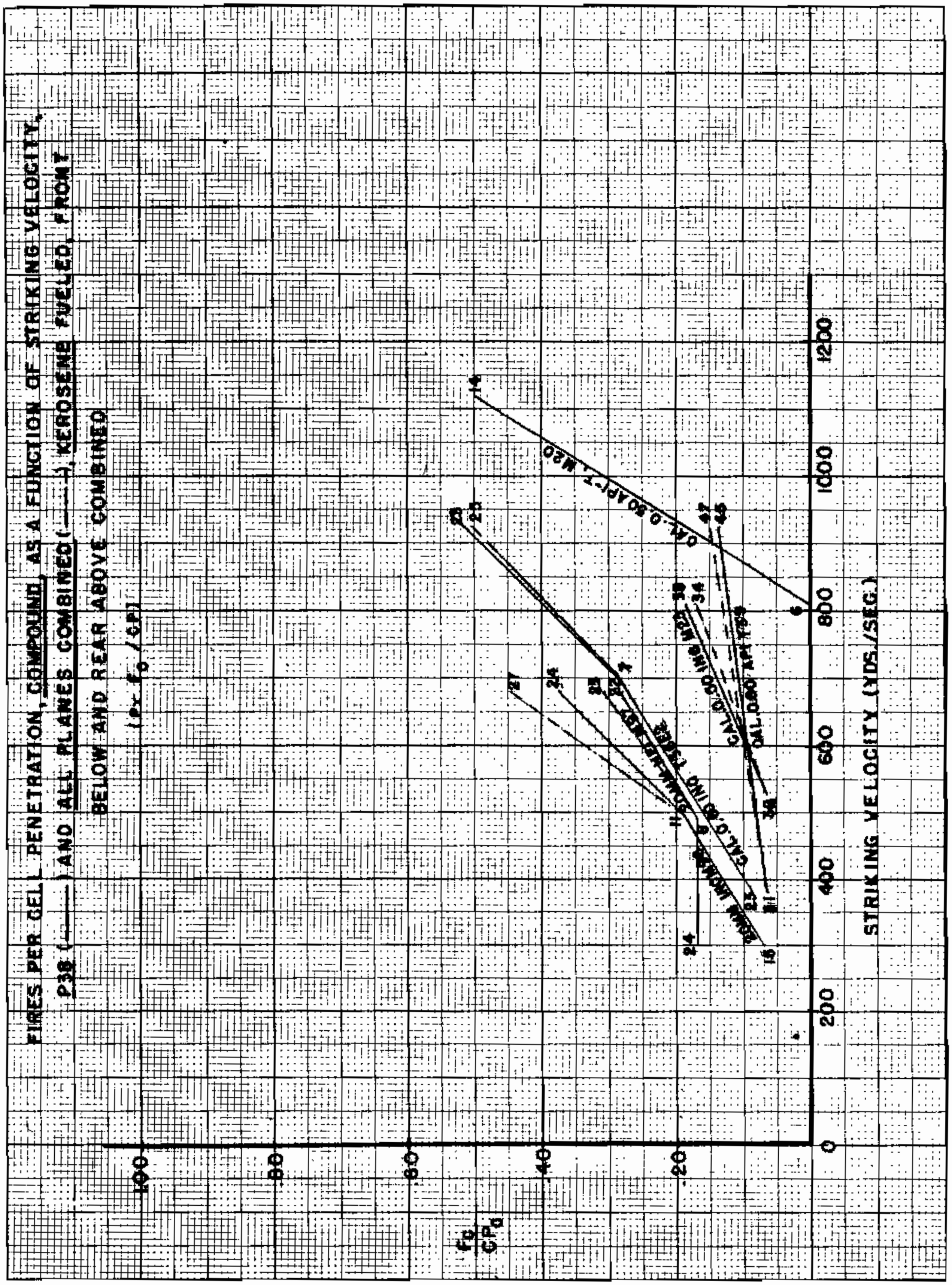

FIRES PER CELL PENETRATION, COMPOUND, AS A FUNCTION OF STRIKING VELOCITY,
P38 (———) AND ALL PLANES COMBINED (– – –), KEROSENE FUELED, FRONT
BELOW AND REAR ABOVE COMBINED
CAL. 0.50 API-T, M20
STRIKING VELOCITY (YDS./SEC.)
0
200
400
600
800
1000
1200
.20
.40
.60
.80
1.00

FIG. 19

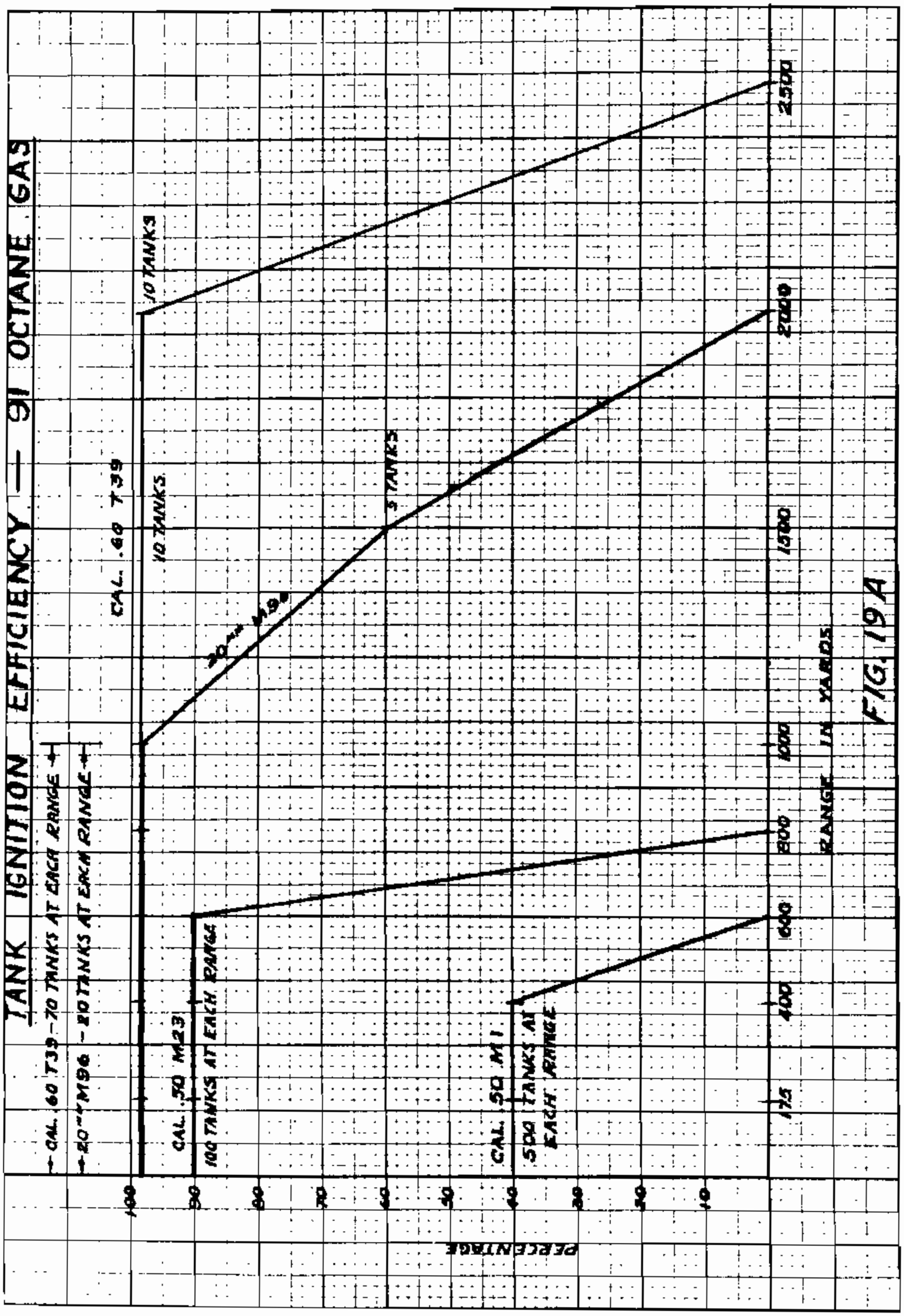

TANK IGNITION EFFICIENCY — 91 OCTANE GAS
CAL. .60 T39 – 70 TANKS AT EACH RANGE
20 MM M96 – 210 TANKS AT EACH RANGE
CAL. .60 T39
10 TANKS
10 TANKS
5 TANKS
20 MM M96
CAL. .50 M23
100 TANKS AT EACH RANGE
CAL. .50 M1
500 TANKS AT EACH RANGE
100
90
80
70
60
50
40
30
20
10
PERCENTAGE
175
400
600
800
1000
1500
2000
2500
RANGE IN YARDS

FIG. 19A

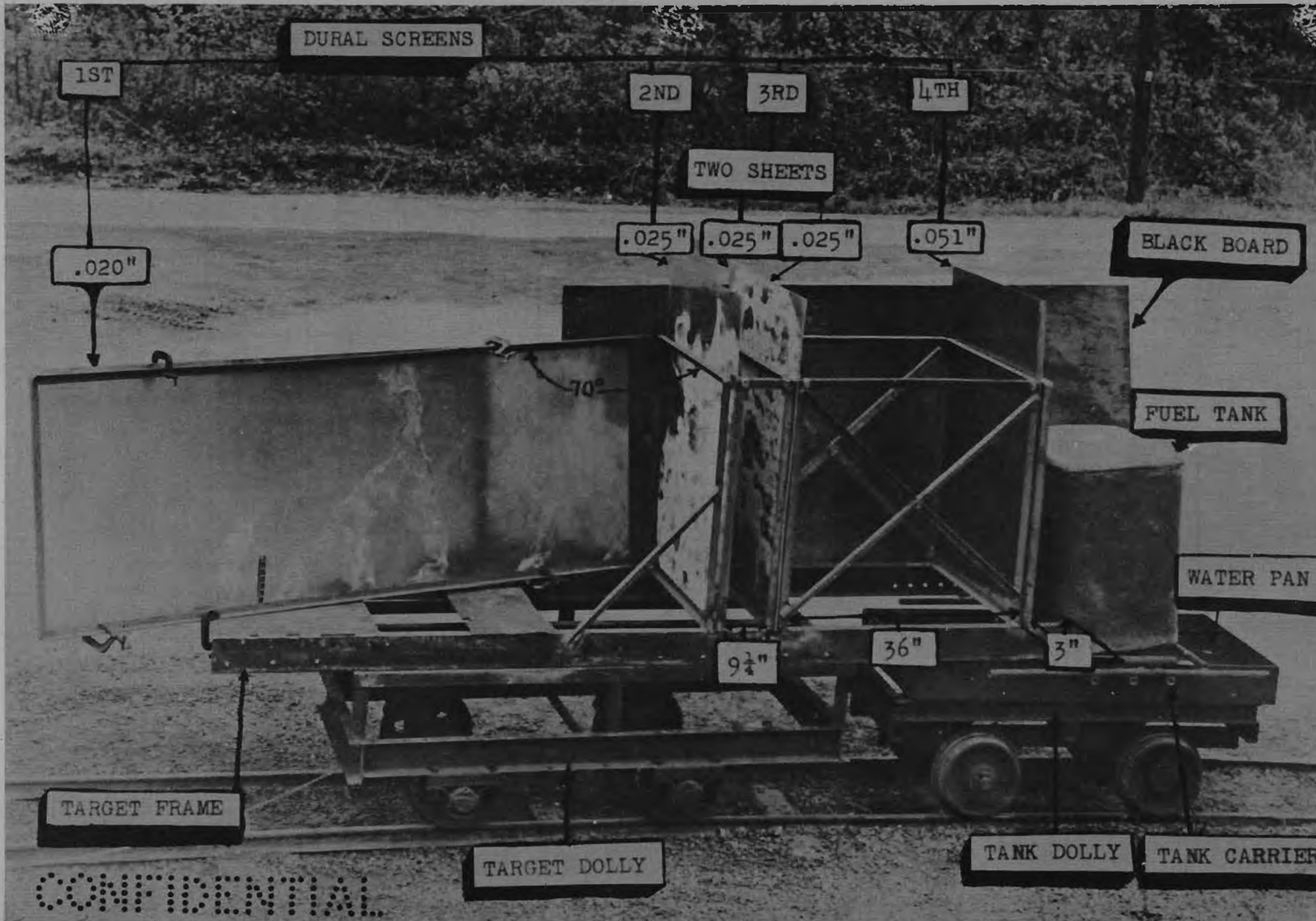


FIG. 19b. Replica Heinkel 111 target frame, filled with dural and a fuel test tank in position. Dural Screen #3 has 2 sheets .025".

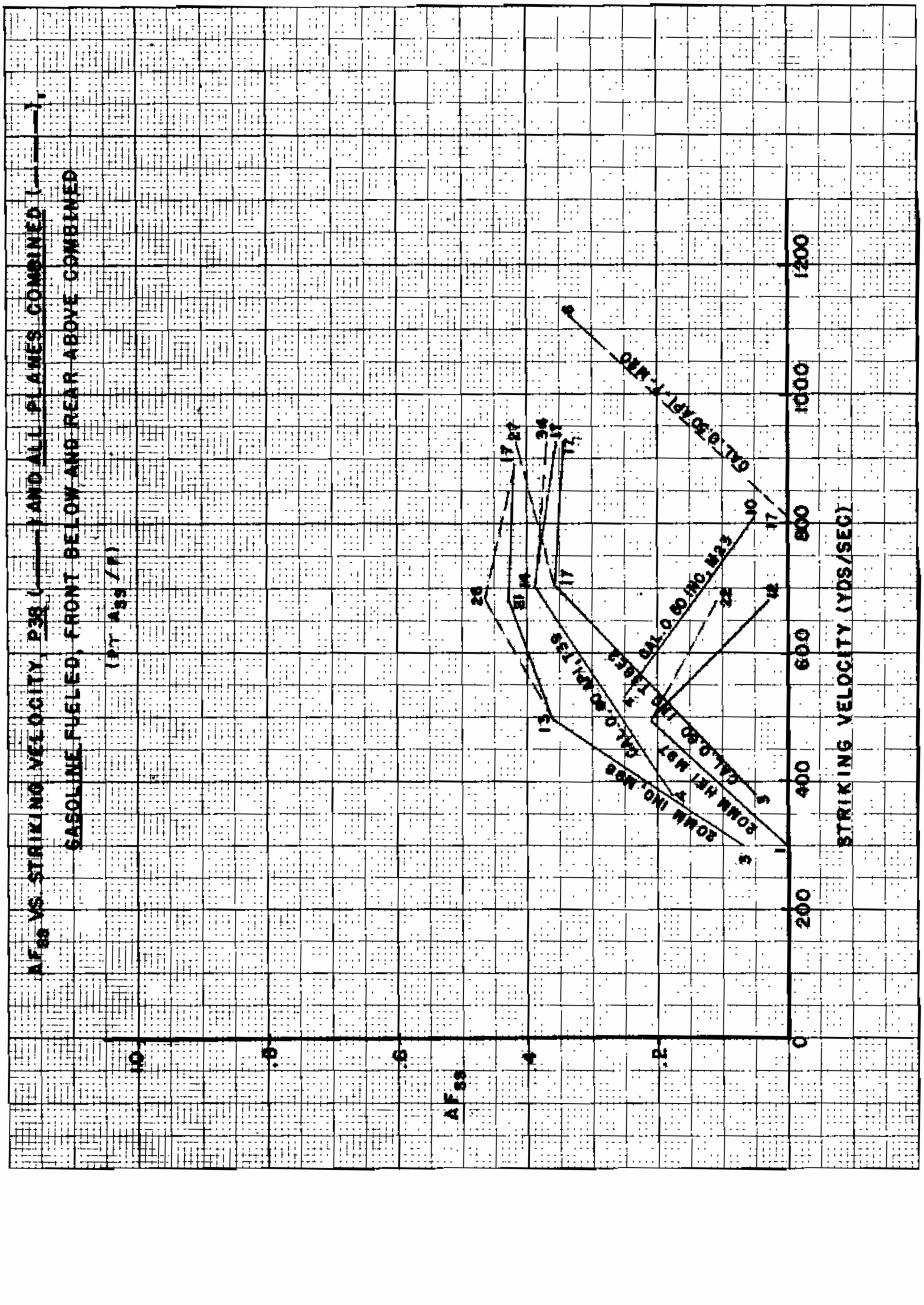

AF$_{SS}$ VS. STRIKING VELOCITY, P38 (———) AND ALL PLANES COMBINED (— — —),
GASOLINE FUELED, FRONT BELOW AND REAR ABOVE COMBINED
AF$_{SS}$
STRIKING VELOCITY (YDS/SEC)
20MM INC. M96
20MM HEI M97
CAL. 0.50 API T32
CAL. 0.50 INC. T48E3
CAL. 0.50 INC. M23
CAL. 0.50
CAL. 0.30 API T-M20

FIG. 20

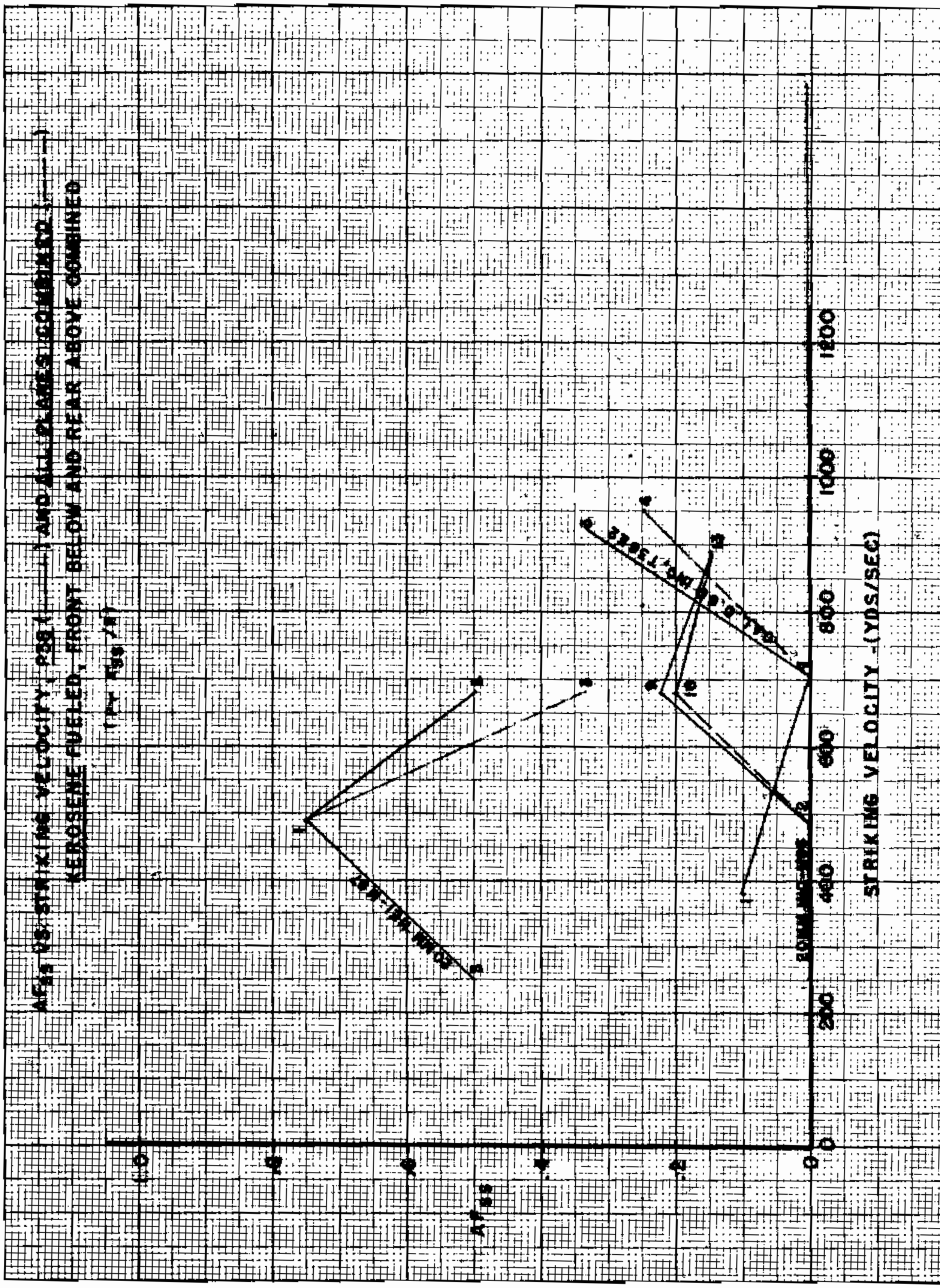

KEROSENE FUELED, FRONT BELOW AND REAR ABOVE COMBINED
STRIKING VELOCITY -(YDS/SEC)
0
200
400
600
800
1000
1200
.2
.4
.6
.8
1.0
AF55

FIG.21

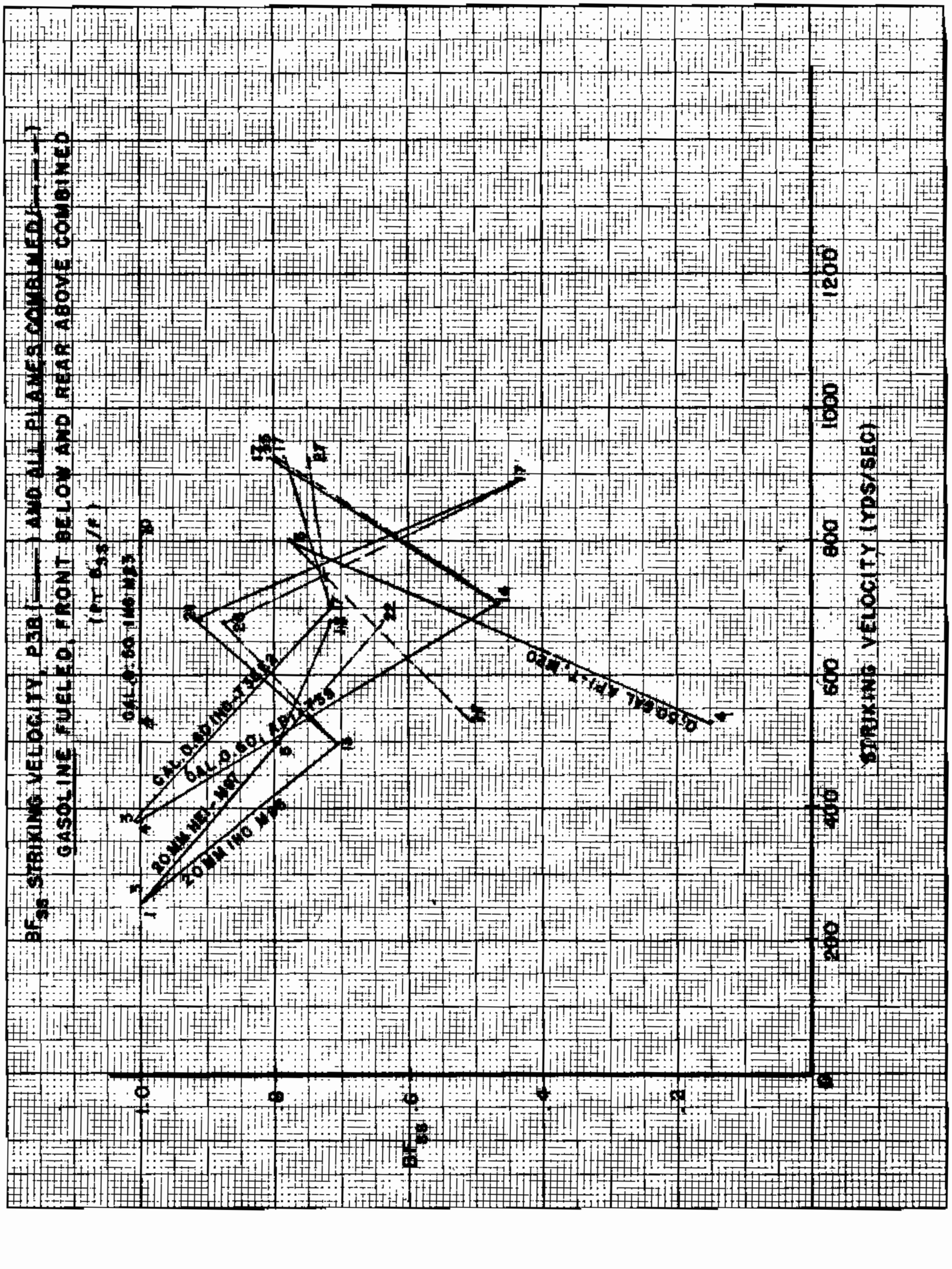

BF55 STRIKING VELOCITY, P38 ( ) AND ALL PLANES COMBINED ( )
GASOLINE FUELED, FRONT BELOW AND REAR ABOVE COMBINED
STRIKING VELOCITY (YDS/SEC)
BF55
200
400
600
800
1000
1200
1.0
.8
.6
.4
.2
0
CAL 0.50 INC M23
CAL 0.60 INC-T M2
CAL 0.60 AP T36
20 MM HEI M97
20 MM INC M96
0.50 CAL API-T M20

FIG. 22

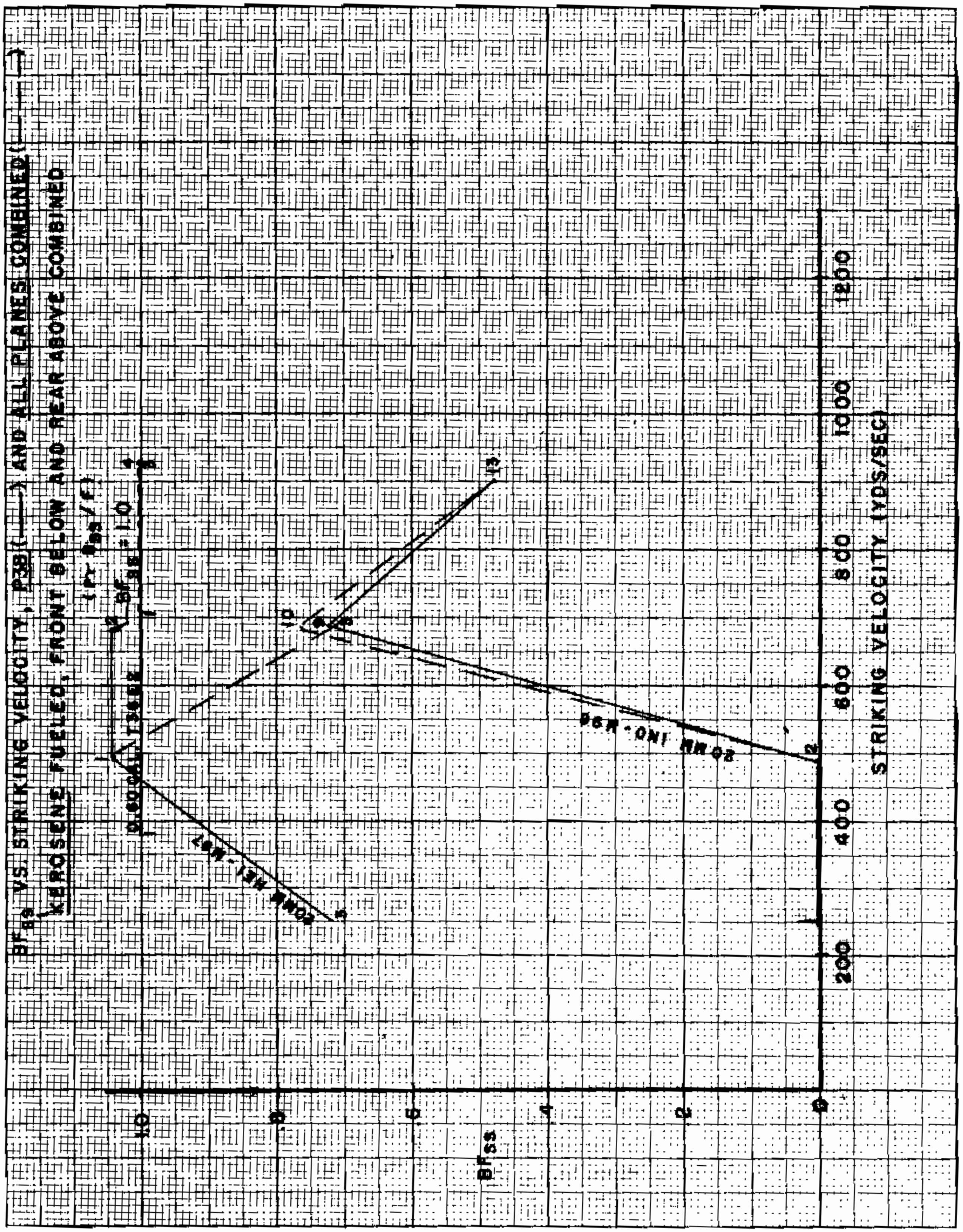

BF VS. STRIKING VELOCITY, P38 ( ) AND ALL PLANES COMBINED ( )
KEROSENE FUELED, FRONT BELOW AND REAR ABOVE COMBINED
20MM HEI-M97
20MM INC-M96
STRIKING VELOCITY (YDS/SEC)
BFss
0
200
400
600
800
1000
1200
.2
.4
.6
.8
1.0

FIG. 23

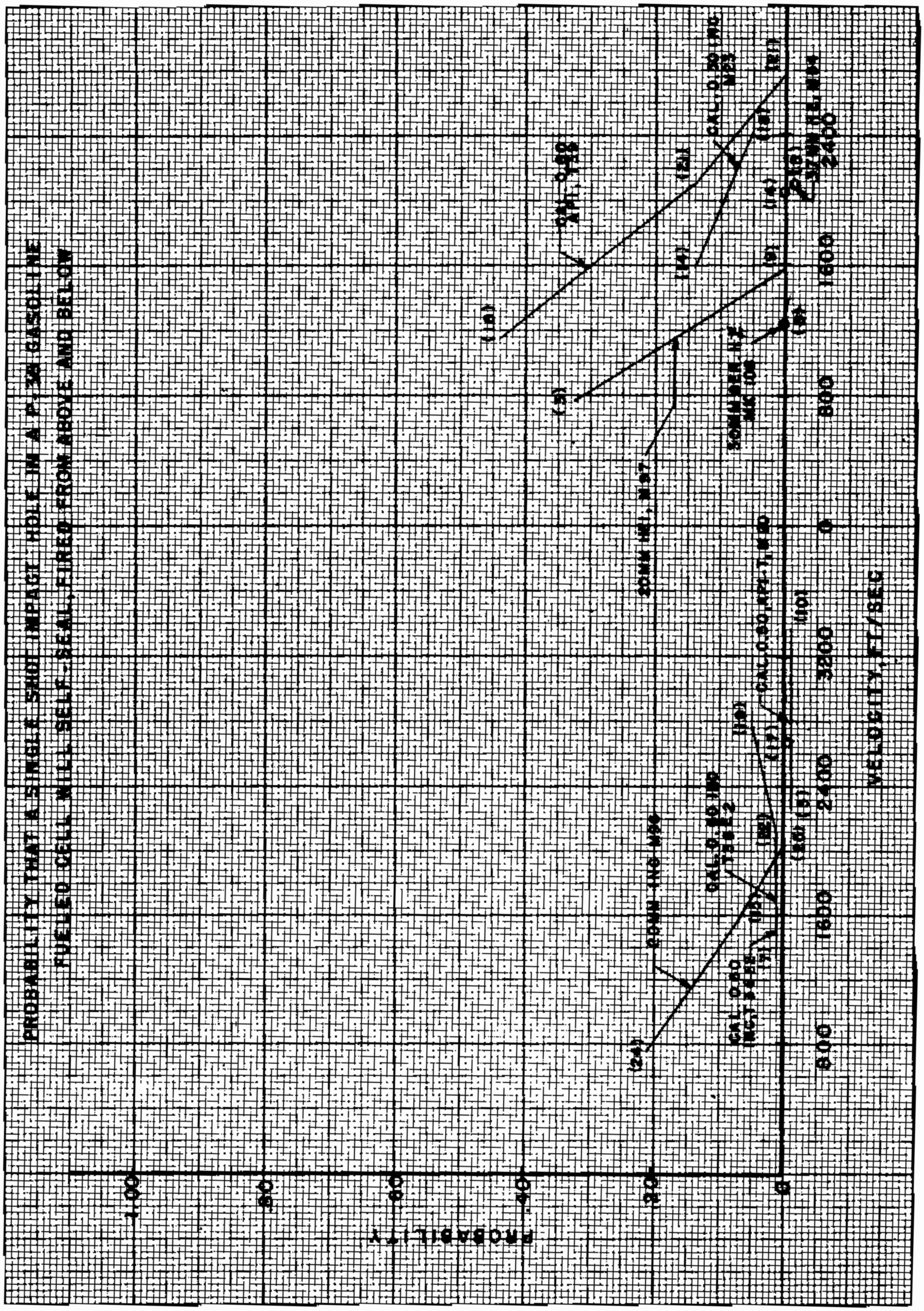

PROBABILITY THAT A SINGLE SHOT IMPACT HOLE IN A P-38 GASOLINE
FUELED CELL WILL SELF-SEAL, FIRED FROM ABOVE AND BELOW
PROBABILITY
1.00
.80
.60
.40
.20
0
20MM ING M96
CAL.0.50 INC T38E2
CAL.0.50 INC,T38E2
CAL.0.50,API-T, M20
20MM HEI, M97
20MM HEI,HZ MK 108
CAL.0.50 API, T29
CAL.0.50 INC M23
37MM HE, M54
800
1600
2400
3200
0
800
1600
2400
VELOCITY, FT/SEC

FIG. 24

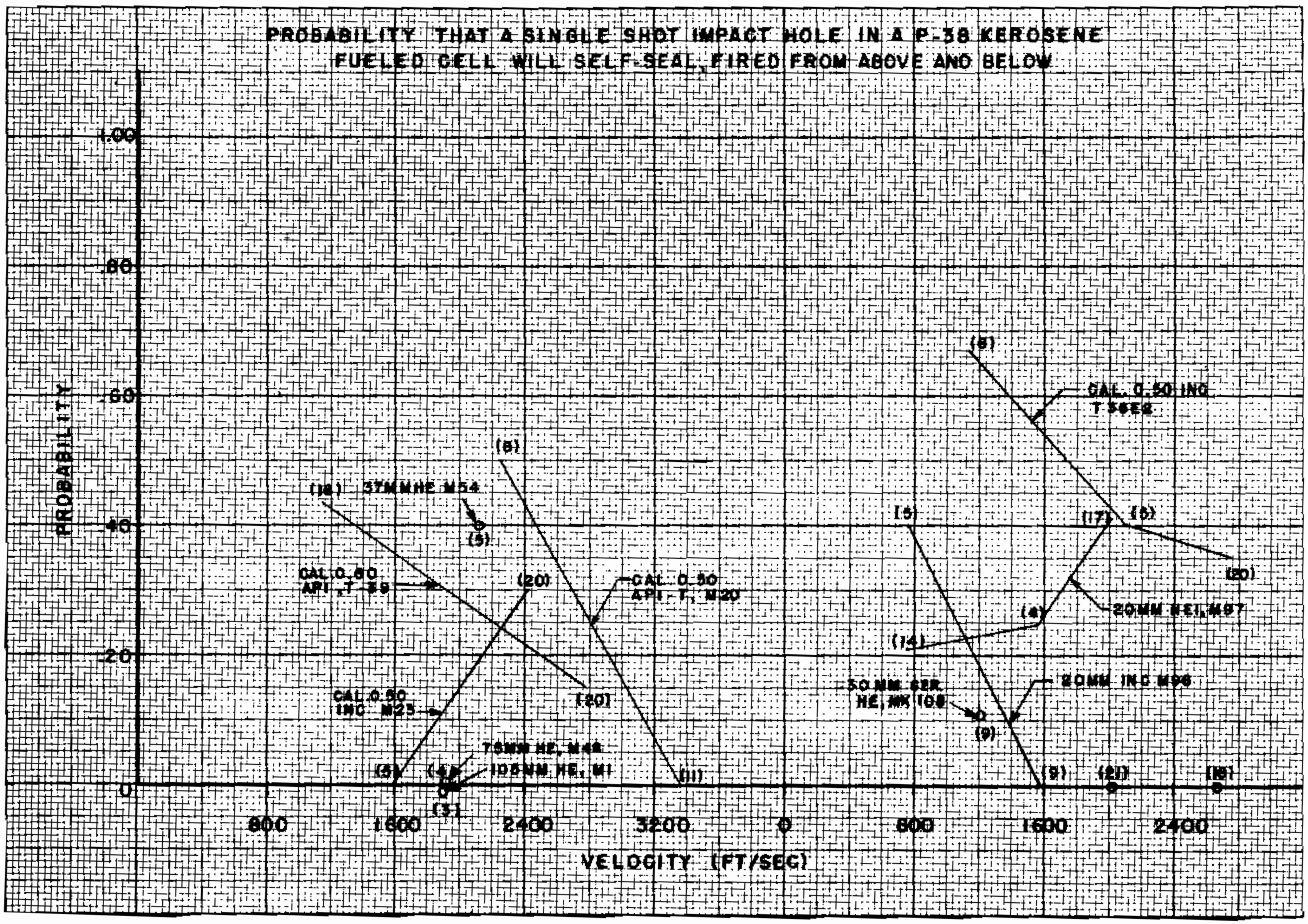

PROBABILITY THAT A SINGLE SHOT IMPACT HOLE IN A P-38 KEROSENE FUELED CELL WILL SELF-SEAL, FIRED FROM ABOVE AND BELOW
PROBABILITY
1.00
.80
.60
.40
.20
0
800
1600
2400
3200
0
800
1600
2400
VELOCITY (FT/SEC)
(18) 37MMHE M54
(5)
(8)
CAL. 0.60 API, T-39
(20)
CAL. 0.50 API - T, M20
(20)
CAL. 0.50 INC. M25
75MM HE, M48
105MM HE, M1
(5)
(4)
(3)
(11)
(8)
CAL. 0.50 INC T36E8
(5)
(17)
(5)
(20)
(4)
20MM HEI, M97
(14)
20MM INC M96
30 MM SER. HE, MK 108
(9)
(9)
(21)
(18)

FIG. 25

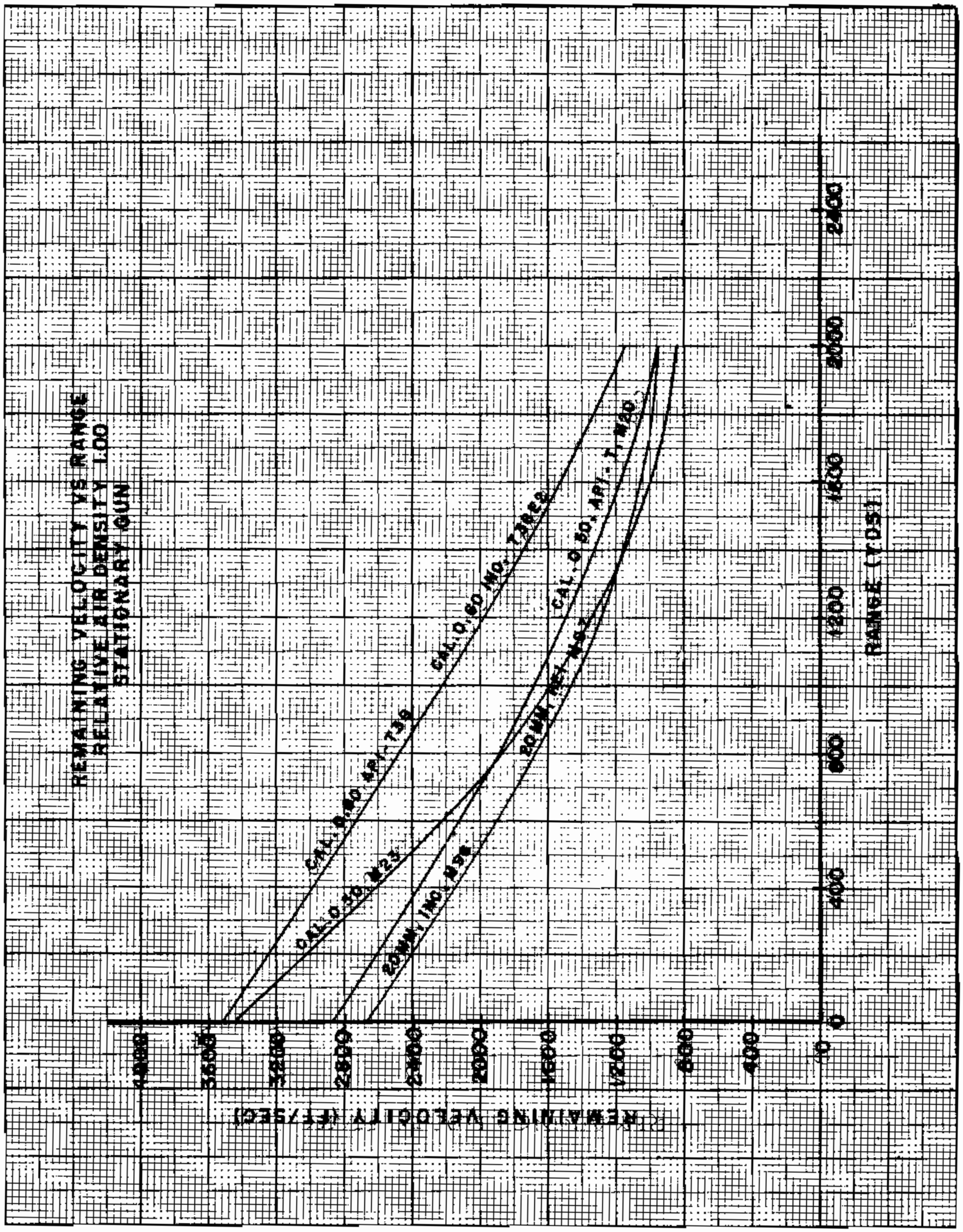

REMAINING VELOCITY VS RANGE
RELATIVE AIR DENSITY 1.00
STATIONARY GUN
CAL. 0.60 API - T39
CAL. 0.60 INC. T38E2
CAL. 0.30 M23
20MM INC. M96
20MM HEI M97
CAL. 0.50 API - T M20
REMAINING VELOCITY (FT/SEC)
RANGE (YDS)
0
400
800
1200
1600
2000
2400
2800
3200
3600
4000

FIG. 26A

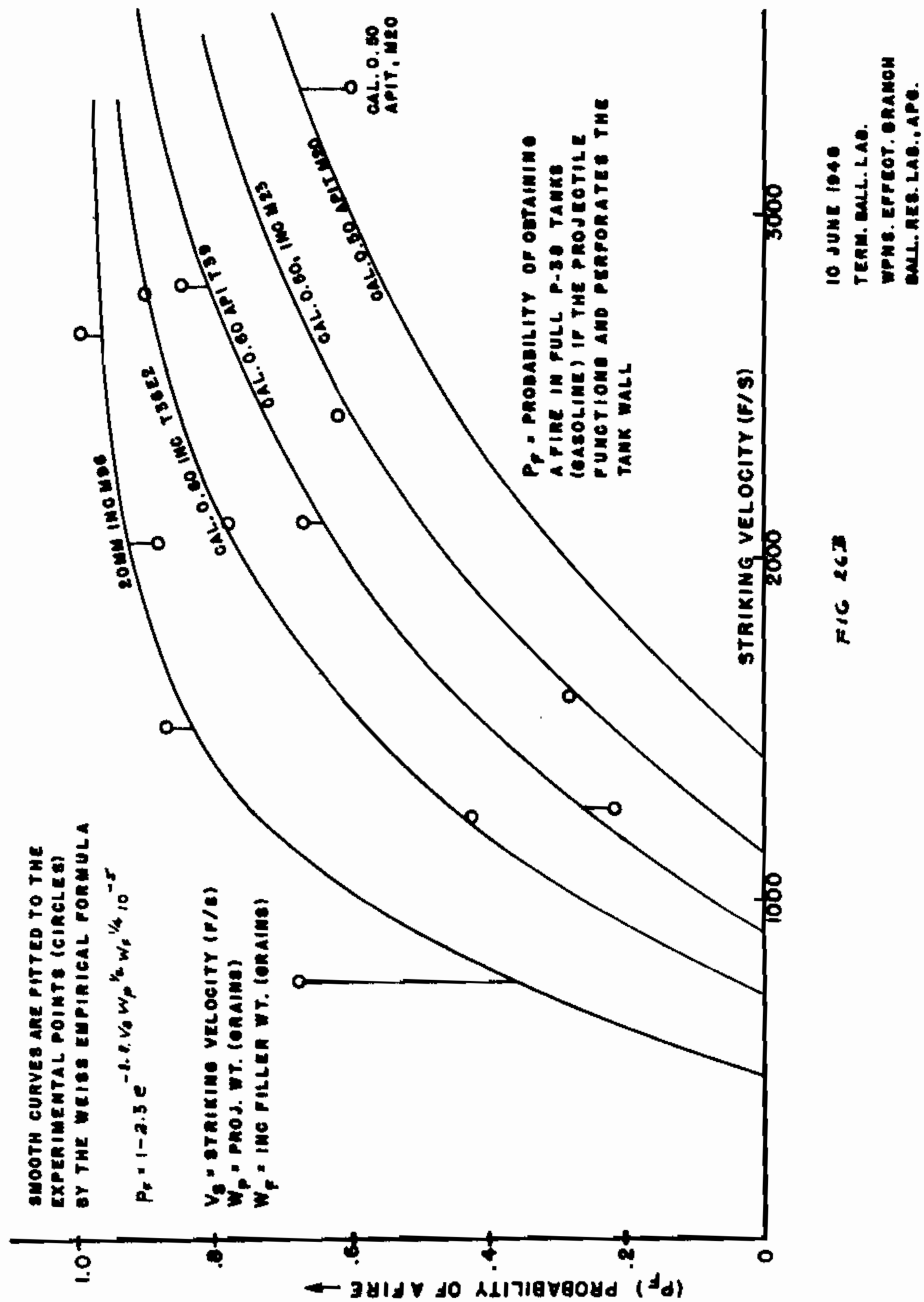

SMOOTH CURVES ARE FITTED TO THE EXPERIMENTAL POINTS (CIRCLES) BY THE WEISS EMPIRICAL FORMULA
$P_F = 1 - 2.5\, e^{-2.8\, V_S W_P^{1/2} W_F^{1/4} 10^{-5}}$
V_S = STRIKING VELOCITY (F/S)
W_P = PROJ. WT. (GRAINS)
W_F = INC FILLER WT. (GRAINS)
20MM INC M96
CAL. 0.60 INC T36E2
CAL. 0.60 API T39
CAL. 0.60, INC M23
CAL. 0.50 APIT M20
CAL. 0.50 APIT, M20
P_F = PROBABILITY OF OBTAINING A FIRE IN FULL P-38 TANKS (GASOLINE) IF THE PROJECTILE FUNCTIONS AND PERFORATES THE TANK WALL
10 JUNE 1946
TERM. BALL. LAB.
WPNS. EFFECT. BRANCH
BALL. RES. LAB., APG.
STRIKING VELOCITY (F/S)
1000
2000
3000
(P_F) PROBABILITY OF A FIRE
0
.2
.4
.6
.8
1.0

FIG 26B

TABLE I

A. Single Shot P38 Fuel Cell Ignition and Leakage for Firings from Front, Below $\theta = 20^{\circ}$, $\phi = 13^{\circ}$

Ammunition Caliber Type	Fuel Type	Striking Velocity ft/sec	Hits on Projected Area Includ. Duds H_{ss}	Hits on Projected Area Exclud. Duds H_{ss}	Perforations of Cell or of Fuel Lines Includ. Duds CP_{ss}	Perforations of Cell or of Fuel Lines Exclud. Duds CP_{ss}	Hits Causing Fires Includ. Duds F_{ss}	Hits Causing Fires Exclud. Duds F_{ss}	Hits Causing Leakage No Fires Includ. Duds L_{ss}	Hits Causing Leakage No Fires Exclud. Duds L_{ss}	Including Duds $\frac{F_{ss}}{H_{ss}}$	Including Duds $\frac{L_{ss}}{H_{ss}}$	Including Duds $\frac{CP_{ss}}{H_{ss}}$	Including Duds $\frac{L_{ss}}{CP_{ss}}$	Including Duds $\frac{F_{ss}}{CP_{ss}}$	Excluding Duds $\frac{F_{ss}}{CP_{ss}}$	Average Assessments of Fire $\bar{A}_{F_{ss}}$	Average Assessments of Fire $\bar{B}_{F_{ss}}$	Average Assessments of Fire $\bar{C}_{F_{ss}}$
Cal. 50 Inc, M23	Gasoline	2430	12	12	10	10	4	4	6	6	.333	.500	.833	.600	.400	.400	.15	1.00	.25
		1590	8	8	6	6	2	2	3	3	.250	.375	.750	.500	.333	.333	.00	1.00	.00
	Kerosene	2430	10	10	10	10	1	1	7	7	.100	.700	1.000	.700	.100	.100	.25	1.00	.00
		1590	5	3	4	2	0	0	4	2	.000	.800	.800	1.000	.000	.000	--	--	--
Cal. 50 API-T, M20	Gasoline	3360	12	12	10	10	6	6	4	4	.500	.333	.833	.400	.600	.600	.33	.77	.33
	Kerosene	3360	15	15	11	11	3	3	8	8	.333	.533	.733	.727	.272	.272	.67	.70	.67
Cal. 60 API, T-39	Gasoline	2770	12	12	11	11	10	10	1	1	.833	.125	.916	.091	.909	.909	.50	.94	.49
		2100	7	7	7	7	5	5	0	0	.714	.000	1.000	.000	.714	.714	.72	1.00	.80
		1140	19	18	14	15	3	3	4	4	.158	.211	.842	.250	.188	.200	.23	1.00	.00
	Kerosene	2770	11	11	9	9	0	0	9	9	.000	.818	.818	1.000	.000	.000	--	--	--
		1140	14	11	14	11	0	0	8	8	.000	.572	1.000	.572	.000	.000	--	--	--
Cal. 60 Inc, T36E2	Gasoline	2770	8	8	7	7	5	5	1	1	.625	.125	.875	.142	.714	.714	.350	.88	.40
		2100	15	15	14	14	10	10	4	4	.667	.267	.933	.286	.714	.714	.300	.65	.38
		1140	9	4	2	2	1	1	1	1	.111	.111	.222	.500	.500	.500	.000	1.00	.00
	Kerosene	2770	14	14	11	11	3	3	7	7	.214	.500	.786	.636	.273	.273	.33	1.00	.38
		1140	11	7	6	4	1	1	2	1	.091	.182	.545	.333	.167	.250	.10	1.00	.00
20mm HEI, M97	Gasoline	2050	4	4	4	4	3	3	1	1	.750	.250	1.000	.250	.750	.750	.33	.67	.33
		1560	6	5	6	5	2	2	4	3	.333	.667	1.000	.667	.333	.400	.02	.50	.00
	Kerosene	2050	8	8	7	7	0	0	2	2	.000	.250	.875	.286	.000	.000	--	--	--
		760	22	15	16	12	3	3	10	7	.136	.455	.727	.625	.188	.250	.30	.67	.67
20mm Inc, M96	Gasoline	2670	18	18	17	17	17	17	0	0	.944	.000	.944	.000	1.000	1.000	.41	.44	.37
		2050	18	18	15	15	13	13	2	2	.722	.111	.833	.133	.867	.867	.36	1.00	.35
		1560	10	10	8	8	7	7	1	1	.700	.100	.800	.125	.875	.875	.29	.92	.29
		760	52	32	24	21	12	12	7	4	.231	.135	.462	.292	.500	.571	.37	.58	.56
	Kerosene	2670	16	16	14	16	13	13	3	3	.813	.188	1.000	.188	.813	.813	.15	.44	.14
		2050	12	12	12	12	4	4	8	8	.333	.667	1.000	.667	.333	.333	.50	1.00	.50
		1560	5	5	5	5	0	0	5	5	.000	1.000	1.000	1.000	.000	.000	--	--	--
		760	9	8	4	3	0	0	3	2	.000	.333	.444	.750	.000	.000	--	--	--

B. Single Shot P38 Fuel Cell Ignition and Leakage for Firings from Rear, Above $\theta = 20^{\circ}$, $\phi = 13^{\circ}$

Ammunition Caliber Type	Fuel Type	Striking Velocity ft/sec	Hits on Projected Area Includ. Duds H_{ss}	Hits on Projected Area Exclud. Duds H_{ss}	Perforations of Cell or of Fuel Lines Includ. Duds CP_{ss}	Perforations of Cell or of Fuel Lines Exclud. Duds CP_{ss}	Hits Causing Fires Includ. Duds F_{ss}	Hits Causing Fires Exclud. Duds F_{ss}	Hits Causing Leakage No Fires Includ. Duds L_{ss}	Hits Causing Leakage No Fires Exclud. Duds L_{ss}	Including Duds $\frac{F_{ss}}{H_{ss}}$	Including Duds $\frac{L_{ss}}{H_{ss}}$	Including Duds $\frac{CP_{ss}}{H_{ss}}$	Including Duds $\frac{L_{ss}}{CP_{ss}}$	Including Duds $\frac{F_{ss}}{CP_{ss}}$	Excluding Duds $\frac{F_{ss}}{CP_{ss}}$	Average Assessments of Fire $\bar{A}_{F_{ss}}$	Average Assessments of Fire $\bar{B}_{F_{ss}}$	Average Assessments of Fire $\bar{C}_{F_{ss}}$
Cal. 50 Inc, M23	Gasoline	2450	17	17	8	8	6	6	1	1	.353	.059	.471	.125	.750	.750	.00	1.00	.00
		1590	9	9	8	8	2	2	5	5	.222	.556	.889	.625	.250	.250	.50	1.00	.50
	Kerosene	2450	15	15	10	10	0	0	6	6	.000	.400	.666	.600	.000	.000	--	--	--
		1590	4	4	3	3	0	0	3	3	.000	.750	.750	1.000	.000	.000	--	--	--
Cal. 50 API-T, M20	Gasoline	2250	14	14	5	5	4	4	1	1	.286	.071	.357	.200	.800	.800	.00	.15	.00
	Kerosene	2250	7	7	6	6	0	0	3	3	.000	.428	.857	.500	.000	.000	--	--	--
Cal. 60 API, T39	Gasoline	2770	18	18	10	10	7	7	5	5	.389	.167	.555	.500	.700	.700	.14	.63	.00
		2100	20	20	14	14	9	9	4	4	.450	.200	.700	.286	.643	.643	.33	.63	.22
		1140	5	5	3	3	1	1	2	2	.200	.400	.600	.667	.333	.333	.00	1.00	.00
	Kerosene	2770	12	12	11	11	0	0	8	8	.000	.667	.917	.727	.000	.000	--	--	--
		1140	11	8	6	5	0	0	2	1	.000	.182	.546	.333	.000	.000	--	--	--
Cal. 60 Inc, T36E2	Gasoline	2770	15	15	12	12	12	12	0	0	.800	.000	.800	.000	1.000	1.000	.35	.75	.26
		2100	12	12	8	8	7	7	1	1	.583	.083	.667	.125	.875	.875	.43	.88	.43
		1140	7	7	5	5	2	2	3	3	.286	.429	.714	.600	.400	.400	.08	1.00	.00
	Kerosene	2770	13	13	9	9	0	0	3	3	.000	.231	.692	.333	.000	.000	--	---	--
		2100	6	6	5	5	1	1	5	2	.167	.667	.833	.800	.200	.200	.00	1.00	.00
		1140	8	7	2	2	0	0	0	0	.000	.000	.250	.000	.000	.000	--	--	--
20mm HEI, M97	Gasoline	2050	14	14	10	10	9	9	1	1	.643	.071	.714	.100	.900	.900	.00	.79	.00
		1560	9	8	7	4	3	3	4	1	.333	.444	.778	.571	.429	.750	1.00	1.00	1.00
		760	6	5	5	3	1	1	2	1	.167	.333	.833	.400	.200	.333	.00	1.00	.00
	Kerosene	2050	21	21	10	10	2	2	6	6	.095	.286	.476	.600	.200	.200	.50	1.00	.50
		1560	6	5	5	4	1	1	2	2	.167	.333	.833	.400	.200	.250	.75	1.00	1.00
		760	9	2	9	2	0	0	7	1	.000	.778	1.000	.778	.000	.000	--	--	--
20mm Inc, M96	Gasoline	2050	13	13	10	10	8	8	2	2	.615	.154	.769	.200	.800	.800	.50	.78	.44
		1560	11	11	7	7	6	6	0	0	.545	.000	.636	.000	.857	.857	.46	1.00	.42
		760	9	8	4	3	3	2	1	1	.333	.111	.444	.250	.750	.667	.07	1.00	.02
	Kerosene	2050	15	15	9	9	3	3	6	6	.200	.400	.600	.667	.333	.333	.00	.41	.00
		1560	4	4	4	4	2	2	2	2	.500	.500	1.000	.500	.500	.500	.00	1.00	.00
		760	6	2	4	2	1	1	2	0	.167	.333	.667	.500	.250	.500	.00	1.00	.00
50mm German HE, Mk 108	Gasoline	1250	15	15	8	8	7	7	1	1	.467	.067	.533	.125	.875	.875	.51	.73	.57
	Kerosene	1250	14	14	9	9	5	5	5	3	.357	.214	.642	.333	.555	.555	.40	.67	.38
37mm HE, M54	Gasoline	2100	15	15	5	5	4	4	1	1	.267	.067	.333	.200	.800	.800	.46	1.00	.38
	Kerosene	2100	6	6	5	5	3	3	2	2	.500	.333	.833	.400	.600	.600	.33	.33	.33
75mm HE,48	Kerosene	1920	4	4	4	4	2	2	2	2	.500	.500	1.00	.500	.500	.500	1.00	1.00	1.00
105mm HE,1	Kerosene	1675	3	3	3	3	3	3	0	0	1.000	.000	1.00	.000	1.000	1.000	1.00	1.00	1.00

TABLE 1 (Continued)

C. Compound Shot P38 Fuel Cell Ignition and Leakage for Firings from Front, Below $\theta = 20^{\circ}$, $\phi = 13^{\circ}$

Ammunition Caliber Type	Fuel Type	Striking Velocity ft/sec	Hits on Projected Area Includ. Duds H_c	Hits on Projected Area Exclud. Duds H_c	Perforations of Cell or of Fuel Lines Includ. Duds CP_c	Perforations of Cell or of Fuel Lines Exclud. Duds CP_c	Hits Causing Fires Includ. Duds F_c	Hits Causing Fires Exclud. Duds F_c	Hits Causing Leakage No Fires Includ. Duds L_c	Hits Causing Leakage No Fires Exclud. Duds L_c	Including Duds $\frac{F_c}{H_c}$	Including Duds $\frac{L_c}{H_c}$	Including Duds $\frac{CP_c}{H_c}$	Including Duds $\frac{L_c}{CP_c}$	Including Duds $\frac{F_c}{CP_c}$	Excluding Duds $\frac{F_c}{CP_c}$	Average Assessments of Fire $\overline{A}_{F_c}$	Average Assessments of Fire $\overline{B}_{F_c}$	Average Assessments of Fire $\overline{C}_{F_c}$
Cal. 50 Inc, M23	Gasoline	2430	11	11	9	9	6	6	3	3	.545	.273	.818	.500	.667	.667	.00	1.00	.00
		1590	18	16	14	14	11	11	3	3	.611	.167	.778	.273	.786	.786	.64	1.00	.64
	Kerosene	2430	16	16	14	14	0	0	4	4	.000	.250	.875	.285	.000	.000	--	--	--
		1590	31	30	20	20	2	2	16	16	.065	.516	.645	.800	.100	.100	.02	.55	.00
Cal. 50 API-T, M20	Gasoline	3360	14	14	14	14	13	13	1	1	.929	.071	1.000	.071	.929	.929	.56	.85	.44
	Kerosene	3360	14	14	14	14	7	7	7	7	.500	.500	1.000	.500	.500	.500	1.00	1.00	.79
Cal. 60 API, T39	Gasoline	2770	14	14	11	11	9	9	1	1	.643	.071	.786	.091	.818	.818	.44	.89	.44
		2100	10	10	10	10	6	6	0	0	.600	.000	1.000	.000	.600	.600	.69	.98	.67
		1140	15	15	13	13	8	8	1	0	.333	.066	.867	.076	.615	.615	.31	1.00	.22
	Kerosene	2770	25	25	25	25	3	3	22	22	.120	.880	1.000	.880	.120	.120	.33	.75	.33
		1140	34	31	29	26	2	2	14	13	.059	.411	.853	.483	.069	.077	.00	.05	.00
Cal. 60 Inc, T36E2	Gasoline	2770	4	4	3	3	3	3	0	0	.750	.000	.750	.000	1.000	1.000	.67	1.00	.67
		2100	9	9	9	9	9	9	0	0	1.000	.000	1.000	.000	1.000	1.000	.78	1.00	.78
		1140	8	8	4	4	2	2	2	2	.250	.250	.500	.500	.500	.500	.87	1.00	.63
	Kerosene	2770	14	14	11	11	6	6	4	4	.428	.428	.786	.545	.545	.545	.17	.50	.17
		1140	25	18	16	12	1	1	14	11	.040	.040	.640	.067	.083	.083	.00	.00	.00
20mm HEI, M97	Gasoline	2050	2	2	2	2	2	2	0	0	1.000	1.000	1.000	1.000	1.000	1.000	.50	1.00	.50
		1580	11	8	8	5	4	4	4	1	.364	.500	.727	.363	.500	.800	1.00	1.00	.95
	Kerosene	2050	25	23	11	11	3	3	8	8	.130	.388	.478	.727	.273	.273	.00	1.00	.00
		760	12	7	10	5	2	2	4	3	.167	.333	.833	.400	.200	.400	.75	1.00	.15
20mm Inc, M96	Gasoline	2670	7	7	7	7	6	6	1	1	.857	.143	1.000	.143	.857	.857	.69	.77	.69
		2050	9	9	5	5	5	5	0	0	.555	.000	.555	.000	1.000	1.000	.40	1.00	.40
		1580	1	1	1	1	1	1	0	0	1.000	.000	1.000	.000	1.000	1.000	1.00	1.00	1.00
		760	41	27	26	21	17	17	5	2	.415	.122	.636	.192	.654	.810	.77	.77	.77
	Kerosene	2670	0	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
		2050	16	16	12	12	8	8	4	4	.500	.250	.750	.333	.667	.667	.34	1.00	.14
		1580	11	11	7	7	1	1	6	6	.091	.857	.636	.545	.143	.143	.00	.05	.00
		760	14	8	10	6	0	0	4	2	.000	.285	.714	.400	.000	.000	--	--	--

D. Compound Shot P38 Fuel Cell Ignition and Leakage for Firings from Rear, Above $\theta = 20^{\circ}$, $\phi = 13^{\circ}$

Ammunition Caliber Type	Fuel Type	Striking Velocity ft/sec	Hits on Projected Area Includ. Duds H_c	Hits on Projected Area Exclud. Duds H_c	Perforations of Cell or of Fuel Lines Includ. Duds CP_c	Perforations of Cell or of Fuel Lines Exclud. Duds CP_c	Hits Causing Fires Includ. Duds F_c	Hits Causing Fires Exclud. Duds F_c	Hits Causing Leakage No Fires Includ. Duds L_c	Hits Causing Leakage No Fires Exclud. Duds L_c	Including Duds $\frac{F_c}{H_c}$	Including Duds $\frac{L_c}{H_c}$	Including Duds $\frac{CP_c}{H_c}$	Including Duds $\frac{L_c}{CP_c}$	Including Duds $\frac{F_c}{CP_c}$	Excluding Duds $\frac{F_c}{CP_c}$	Average Assessments of Fire $\overline{A}_{F_c}$	Average Assessments of Fire $\overline{B}_{F_c}$	Average Assessments of Fire $\overline{C}_{F_c}$
Cal. 50 Inc, M23	Gasoline	2430	16	16	16	16	12	12	4	4	.750	.250	1.000	.250	.750	.750	.58	.88	.00
		1590	16	14	9	9	4	4	5	3	.250	.312	.563	.556	.444	.444	.75	1.00	.75
	Kerosene	2430	19	19	19	19	6	6	9	9	.316	.474	1.000	.474	.316	.316	.33	.50	.33
		1590	19	17	12	10	0	0	12	10	.000	.632	.632	1.000	.000	.000	--	--	--
Cal. 50 API-T, M20	Gasoline	2250	19	19	12	12	6	6	3	3	.316	.158	.632	.250	.500	.500	.00	.73	.00
	Kerosene	2250	18	18	16	16	0	0	3	3	.000	.000	.889	.000	.000	.000	--	--	--
Cal. 60 API, T39	Gasoline	2770	8	8	6	6	5	5	1	1	.625	.125	.750	.167	.833	.833	.80	1.00	.55
		2100	8	8	7	7	6	6	1	1	.750	.125	.875	.143	.857	.857	.67	.83	.67
		1140	7	4	6	4	0	0	3	3	.000	.429	.858	.500	.000	.000	--	--	--
	Kerosene	2770	25	25	20	20	3	3	13	13	.120	.120	.800	.150	.150	.150	.50	.80	.12
		1140	4	2	2	1	0	0	2	1	.000	.000	.500	.000	.000	.000	--	--	--
Cal. 60 Inc, T36E2	Gasoline	2770	11	11	9	9	9	9	0	0	.818	.000	.818	.000	1.000	1.000	.64	.69	.44
		2100	11	11	10	10	8	8	0	0	.727	.000	.909	.000	.800	.800	.75	.97	.75
		1140	10	10	7	7	4	4	4	4	.400	.400	.700	.571	.572	.572	.56	1.00	.63
	Kerosene	2770	14	14	12	12	7	7	3	3	.500	.214	.857	.250	.583	.583	.14	.61	.14
		2100	11	10	7	7	2	2	5	5	.182	.455	.636	.714	.287	.287	.00	.50	.00
		1140	9	4	7	3	1	1	6	2	.111		.778		.143	.333	.00	1.00	.00
20mm HEI, M97	Gasoline	2050	11	11	7	7	5	5	1	1	.636	.091	.636	.143	.714	.714	.26	.60	.16
		1580	14	12	10	8	5	5	5	3	.357	.429	.714	.500	.500	.625	.40	.70	.40
		760	11	7	6	5	0	0	2	1	.000	.182	.545	.333	.000	.000	--	--	--
	Kerosene	2050	11	11	11	11	3	5	4	4	.273	.364	1.000	.373	.273	.273	.00	.58	.00
		1580	11	7	6	2	1	1	3	0	.091	.273	.546	.500	.167	.500	.00	1.00	.00
		760	22	9	14	5	2	1	8	1	.091	.364	.636	.572	.143	.200	1.00	1.00	1.00
20mm Inc, M96	Gasoline	2050	16	16	10	10	10	10	0	0	.625	.000	.625	.000	1.000	1.000	.80	.95	.75
		1580	3	3	3	3	2	2	0	0	.667	.000	1.000	.000	.667	.667	1.00	1.00	1.00
		760	5	4	4	3	0	0	2	2	.000	.400	.800	.500	.000	.000	--	--	--
	Kerosene	2050	18	16	12	12	1	1	9	9	.056	.500	.667	.750	.083	.083	1.00	1.00	1.00
		1580	5	5	4	4	1	1	2	2	.200	.400	.800	.500	.250	.250	1.00	1.00	1.00
		760	6	3	5	2	1	1	2	1	.167	.333	.833	.400	.200	.500	.00	.00	.00
30mm German HE, Mk 108	Gasoline	1250	2	2	2	2	1	1	0	0	.500	.000	1.000	.000	.500	.500	.00	.75	1.00
	Kerosene	1250	11	11	7	7	7	7	0	0	.636	.000	.636	.000	1.000	1.000	.29	.49	.51
37mm HE, M54	Gasoline	2100	1	1	0	0	0	0	0	0	.000	.000	.000	.000	.000	.000	--	---	--
	Kerosene	2100	4	4	3	3	2	2	1	1	.500	.250	.750	.333	.667	.667	.50	.50	.50
75mm HE, M48	Kerosene	1920	0	0	-	-	-	-	-	-	--	--	--	--	--	--	--	--	--
105mm HE, M1	Kerosene	1875	0	0	-	-	-	-	-	-	--	--	--	--	--	--	--	--	--

SUPPLEMENTARY TESTS

The principal "optimum caliber" tests are not of themselves sufficient if results are to be useful in the determination of the vulnerability of future aircraft to present or future types of ammunition. With regard to igniting aircraft fuel tanks, it is particularly important to obtain more basic data than could be obtained from observation of impacting projectiles on aircraft wings. The probability of igniting fuel tanks is sensitive to changes in type of incendiary functioning, fuzing of HE shell and environmental conditions. To obtain the necessary additional data, a number of supplementary tests have been designed with more limited and specialized objectives than the principal firings against aircraft. With these tests, it should be possible to observe more closely the behavior of the factors affecting ignition and to achieve greater control over significant variants. Some of these tests are briefly described in the following pages. It is hoped to present fully detailed reports after their completion.

INCENDIARY FUNCTIONING CHARACTERISTICS

There is in progress a series of firings of incendiary ammunition against various thicknesses of dural plate for impacts at several obliquities. The purpose of these tests is to observe (1) how the probability of functioning varies with type of projectile, thickness of dural plate, striking velocity, obliquity and the effect of spaced plate and (2) the characteristics of functioning, such as the position of initial flash after impact, and the length and the duration of flash.

Ultra-high speed motion pictures are used to give the duration of flash and still photographs yield details regarding the other characteristics of functioning. Figures 27 and 28 depict two typical observations.

There have been fired to date in this program, at normal obliquity, the Cal. 0.60 API, T39, Cal. 0.60 INC, T36E2, 20mm INC, M96 and the 20mm HEI, M97 against dural plate varying in thickness from .051" to .125" and at ranges of 175, 400, 800 and 1500 yards. These same projectiles have also been fired at 70° from normal against dural plate of .025" and .051" at ranges of 175 and 400 yards.

A short summary of preliminary results appears below.

Extreme Variations Observed in Incendiary Functioning Tests
Preliminary Results

Functioning Characteristic	Variation
Distance from target plate to first sign of flash	0 ft. to 10 ft.*
Distance from target plate to heart of flash	0 ft. to 14 ft.*
Length of flash	1 ft. to greater than field of view which was 16 ft.
Duration of flash when it did occur	2 to 56 milli-seconds.

*Some rounds did not begin to function until outside the field of view of the camera (16 ft.). One of these was visually estimated as functioning 35 feet behind the plate.

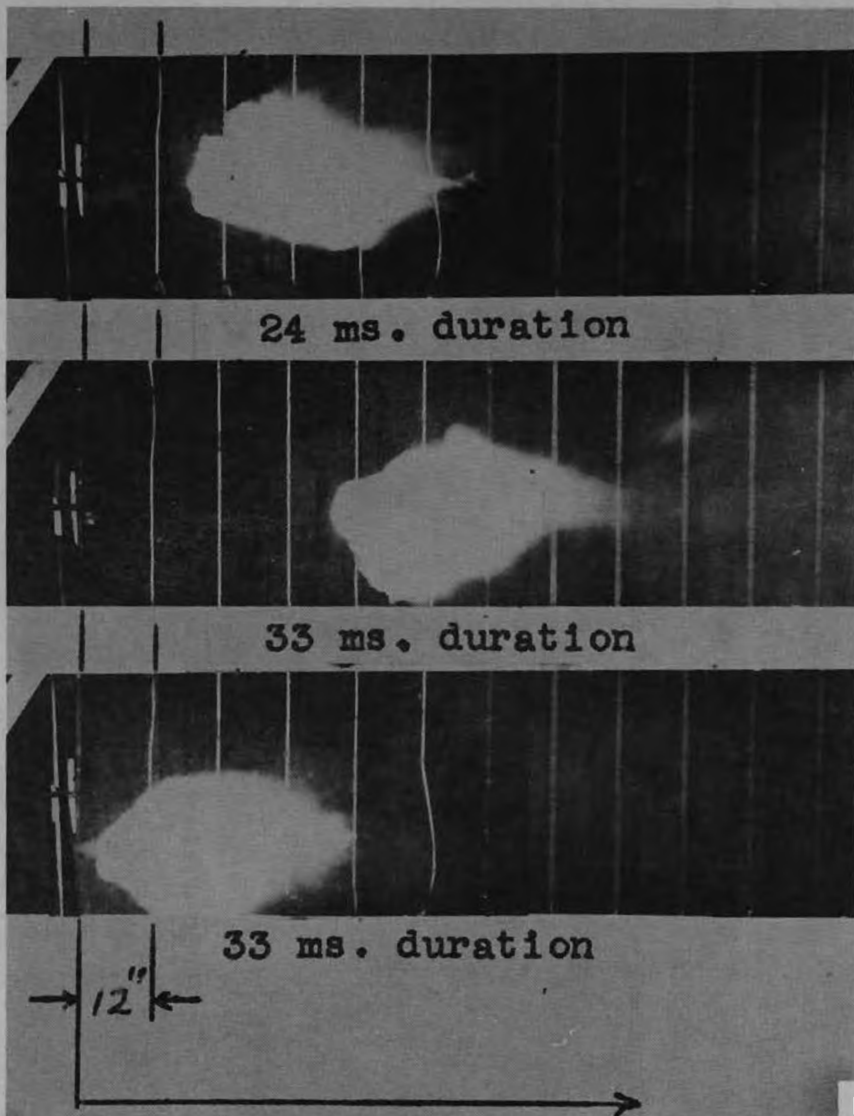


FIG. 27. Function of Ctg., API, Cal. .60, Lot FA 16, after impacting a .125" dural target set normal to the line of fire and at a range of 400 yards.

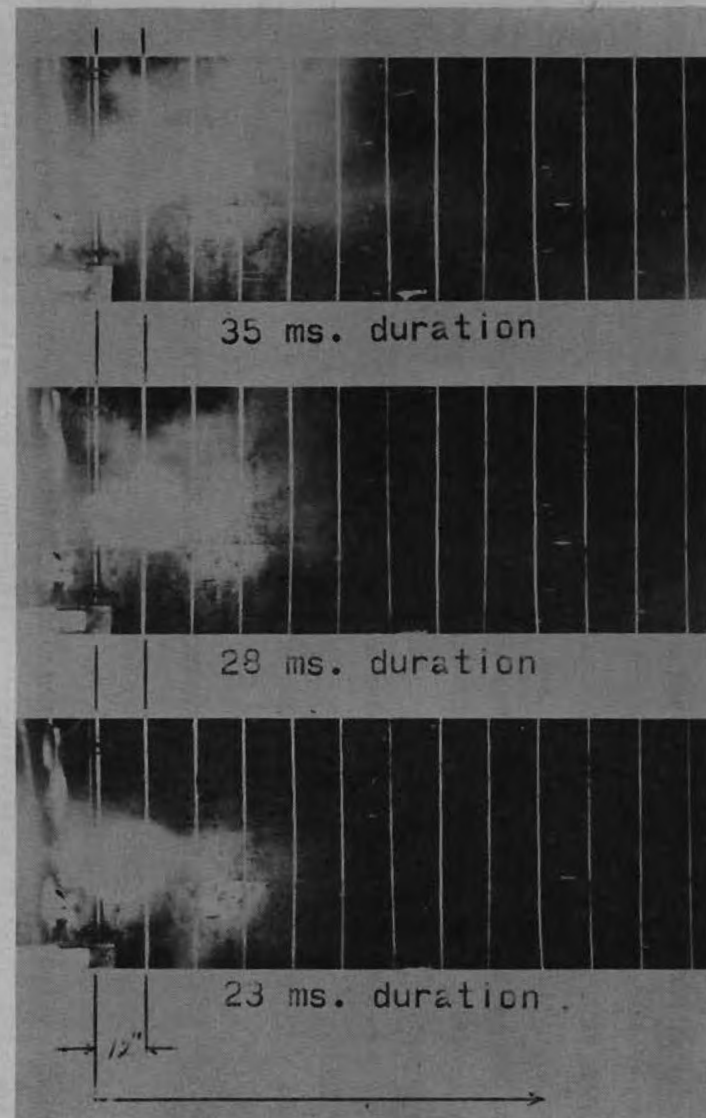


FIG. 28. Function of Ctg., API, Cal. .60, Lot FA 16, after impacting a .125" dural target set normal to the line of fire and at a range of 800 yards.

The importance of the results of these tests on incendiary functioning characteristics cannot be overestimated.

On the one hand, when coupled with tests on fuel spray emergence from impact holes, they provide the designer of incendiary ammunition with the data he needs to understand the variability in the fuel cell igniting efficiency of various types of incendiary bullets and a means for prediction of performance before costly tests against fuel cells are performed. Also, tests such as these may reveal much more concerning the probable effectiveness of a lot of incendiary ammunition up for acceptance, than firings against replica fuel cell targets. That this has been a major concern of the Ordnance Department during the war is evident from the important tests conducted at Frankford Arsenal and at Aberdeen to study the mechanics of ignition and incendiary functioning.[1, 2, 3]

On the other hand, these results are highly significant to the designer of aircraft fuel installations. For he may take advantage of this variability in incendiary functioning and arrange the fuel tanks so that, under most conditions of attack, the functioning will occur within the tank rather than between the skin and the tank. Some distance between skin and tank is advisable so that petalling of the skin around the impact hole is kept from holding open a hole in the tank and preventing sealing. It is unfortunate that the prevention of ignition of fuel cells by fragment impact indicates a need for greater distance between skin and tank. Hence, a choice of design will thus depend to a great extent on the type of attack expected. Bombers are more likely to be subject to fragment impacts than fighters. The degree of this difference may be indicated by intelligence reports and is a subject for a thorough study of its own.

FUEL TANK SPRAY STUDIES

Ignition of fuel tanks by incendiary bullet impacts below the fuel level occurs on the outside of the tank where the vapor-air mixture is lean enough for combustion. The incendiary projectile will not, with present incendiaries, cause a kill by ignition within the fuel tank below the fuel level. The incendiary must maintain temperatures above the ignition temperature of the combustible vapor-air mixture resulting on the outside of the tank as a result of the perforation of the tank wall. This ignition temperature must be maintained long enough to ignite the fuel spray emerging from the impact hole. The seriousness of the resulting fire depends thereafter on the amount of fuel feeding the fire and hence on the degree of self-sealing. Often the initial ignition burns or chars the tank material to such an extent as to defeat the self-sealing of the tank. The study of the duration of incendiary flashes (and also flashes resulting from fragment impacts) should therefore be supplemented by the study of spray emission from fuel tanks after impact.

[1] FA R-567 "High Speed Motion Picture Study of Ignition of German Type Self-Sealing Tanks Placed to Rear of Heinkel Replica Target", E. R. Thilo, Nov. 1944.

[2] APG FR S-39192 - O.P. 5374, "To Investigate the Application of High Speed Motion Pictures to the Study of Flash and Tank Ignition Characteristics of Cartridge, Incendiary, Cal. .50 M1.

[3] The bibliography and description of incendiary research and development contained in the Ordnance Department Record of Research and Development in Small Arms Ammunition loc. cit.

The fact that fuel tank ignition usually occurs as a result of ignition of the vapor air mixture on the outside of the tank has been considered by the Air Materiel Command at Wright Field in their design of fuel tank installations,[1] by the Germans in their recommendations for improved weapons for use against aircraft,[2] and by the Ordnance Department in design of incendiary ammunition.[3]

The formation and ignition of liquid sprays from experimental tanks has been studied by the British.[4, 5, 6, 7, 8] Unfortunately this work, so excellently begun, does not appear to have been continued to yield the delays before spray emergence as a function of mass, striking velocity, type of tank and the degree to which it is filled. A study to determine the effect of these variables on the liquid spray has been initiated at Aberdeen and recently at the University of Denver by contract from the Ordnance Department. Suitable pictures are obtained by use of sunlight, but equipment permitting use of an indoor range has not yet been available for this test.

To obtain the pictures of the liquid spray, a series of ultra-high speed motion pictures (about 4000 frames per second) were made of the bullet impact into a water-filled self-sealing fuel tank. The camera was placed perpendicular to and approximately twenty feet to one side of the line of fire at a point even with the face of the fuel cell. Two mirrors, one above and one below the line of fire, were used to reflect sunlight onto the impact surface of the tank and to illuminate a two foot distance in front of the tank. A black background was used. The camera and lighting arrangement is shown in Figure 29.

It had earlier become apparent, from a series of microflash pictures taken in preliminary tests, that not all self-sealing fuel tanks were suitable for use as targets in liquid spray studies. Those tanks with relatively thick outer layers of celastic or other non-rubber material included for structural strength were not suitable for spray tests with the present photographic technique. This latter type of tank construction is fairly typical of so-called rigid, non-metallic tanks. The so-called collapsible tanks usually have 2 layers of rayon fabric on the outside. These however, are usually quite thin compared to the outer layers of the rigid tank.

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[1] TSEPP-144-1698, "Summary of Data on Fires and Explosions in Aircraft Fuel Tanks," 13 Sept 1946.

[2] Ministry of Supply, Reports and Translations No. 835, 1 May 1947, "New Methods for the Improvement of Anti-Aircraft Efficiency," by Voss.

[3] Record of Army Ordnance Research and Development, Volume 2, Book 2, "Small Arms Ammunition," Office of the Chief of Ordnance, Research and Development Service, January 1946, page 57.

[4] AC 7290, SIMR E144, Jan 1945, "Penetration of Fuel Tanks by Projectiles. I. Formation and Ignition of Liquid Sprays," by H. C. Grimshaw.

[5] AC 7863, SIMR E145, Feb 1945, II. "Formation of Liquid Sprays, Snapshot Photography," by W. C. F. Shepherd and V. O. Hardy.

[6] AC 7865, SIMR E146, Feb 1945, III. "Formation of Liquid Sprays From Experimental Tanks," by W. C. F. Shepherd and V. O. Hardy.

[7] SIMR E153, June 1945, IV. "Characteristics of the Sprays Produced by 0.303 In. Bullets in Stable Flight," by W. C. F. Shepherd and V. O. Hardy.

[8] SIMR E155, June 1945, V. "Liquid Motion Set Up by 0.303 In. Bullets Fired Downwards into Fuel Tanks," by W. C. F. Shepherd and V. O. Hardy.

FIG. 29. Ultra-High Speed Camera Set-up for Photographing the After Effects of Bullet Entry into Fuel Cells. Mirrors are used to reflect sunlight onto the face of the fuel cells.

The Goodrich B-25 bomb bay tank is a rigid type tank with a thick outer ply of fabric. The results of firing into an empty Goodrich tank with Cal. 0.50 ball ammunition are illustrated in Figure 30. The pictures were taken at 4000 frames per second. The first two strips show the bullet impact and the succeeding 11 frames. Evidently a spray of tank material appears in less than 1/4 millisecond after impact. Strip 3 shows the appearance of this spray 12 and 13 milliseconds after impact. Strip 4 shows the spray after 40 milliseconds. The maximum spray appears in this strip. Clearly, this type of tank is unsuitable for a study of liquid spray without major modification of technique.

Figure 31 shows the results of a similar impact on an empty U.S. Rubber B-25 bomb bay tank. This tank has a relatively thin outer fabric layer. The pictures show that this tank would be suitable for liquid spray studies, since a limited amount of spray appears from the tank wall.

Strips 1 and 2 of Figure 32 show the results of impact by Cal. 0.50 ball ammunition on an empty replica Heinkel tank made in this country. This tank does not have a thick outer ply of fabric and there appears very little spray from the tank wall. Strip 1 shows the impact and strip 2 is a typical of all the succeeding frames.

Strips 3 and 4 of Figure 32 and the strips in Figure 33 depict the results of firing into a water-filled Heinkel replica tank. The liquid spray first appears as shown by the arrow in strip 4 of Figure 32. This was at the 29th frame or about 7 milliseconds after impact. The development of this spray is shown in the strips of Figure 33. In strip 2 of Figure 33 a second spray is evident. This spray comes from the tank filler cap which ruptured as a result of impact. The maximum development of the visible spray in Figure 33 is about two feet.

It is expected that the results of the series of fuel tank spray tests with bullets and fragments of various masses and striking velocities will be of great value when coupled with fragment flash results and the incendiary bullet functioning tests described earlier. Also, whereas the photographic observations of incendiary bullet functioning may be a valuable technique for evaluating production lots of incendiary ammunition, the photographic observations of fuel tank behavior upon bullet impact may greatly assist the evaluation of fuel tanks presented for acceptance testing.

EFFECT OF HIGH EXPLOSIVES ON FUEL TANKS

Firings of bare TNT charges both within and on the outside of gasoline filled fuel tanks have been nearly completed. For bare TNT charges it appears that as much as one pound of TNT placed at the geometrical center of a gasoline-filled B-17 feeder tank will completely demolish the tank but will not result in fire. The lowest weight of charge used was 1/16 pound TNT. This charge also caused leakage but no fire. A one pound charge of black powder was also detonated within a B-17 fuel cell, on the theory that the slower burning black powder should result in temperatures above the ignition temperature at the outside of the tank where a proper vapor-air mixture for ignition would be found. However, this charge likewise resulted in leakage without ignition.

Tests have been conducted to determine the effect of static firing of bare TNT charges placed within B-17 wings but at 12 different distances from fully loaded gasoline fuel cells. The weights of charges used at these respective positions were separately increased at each position until a fire assessed as causing

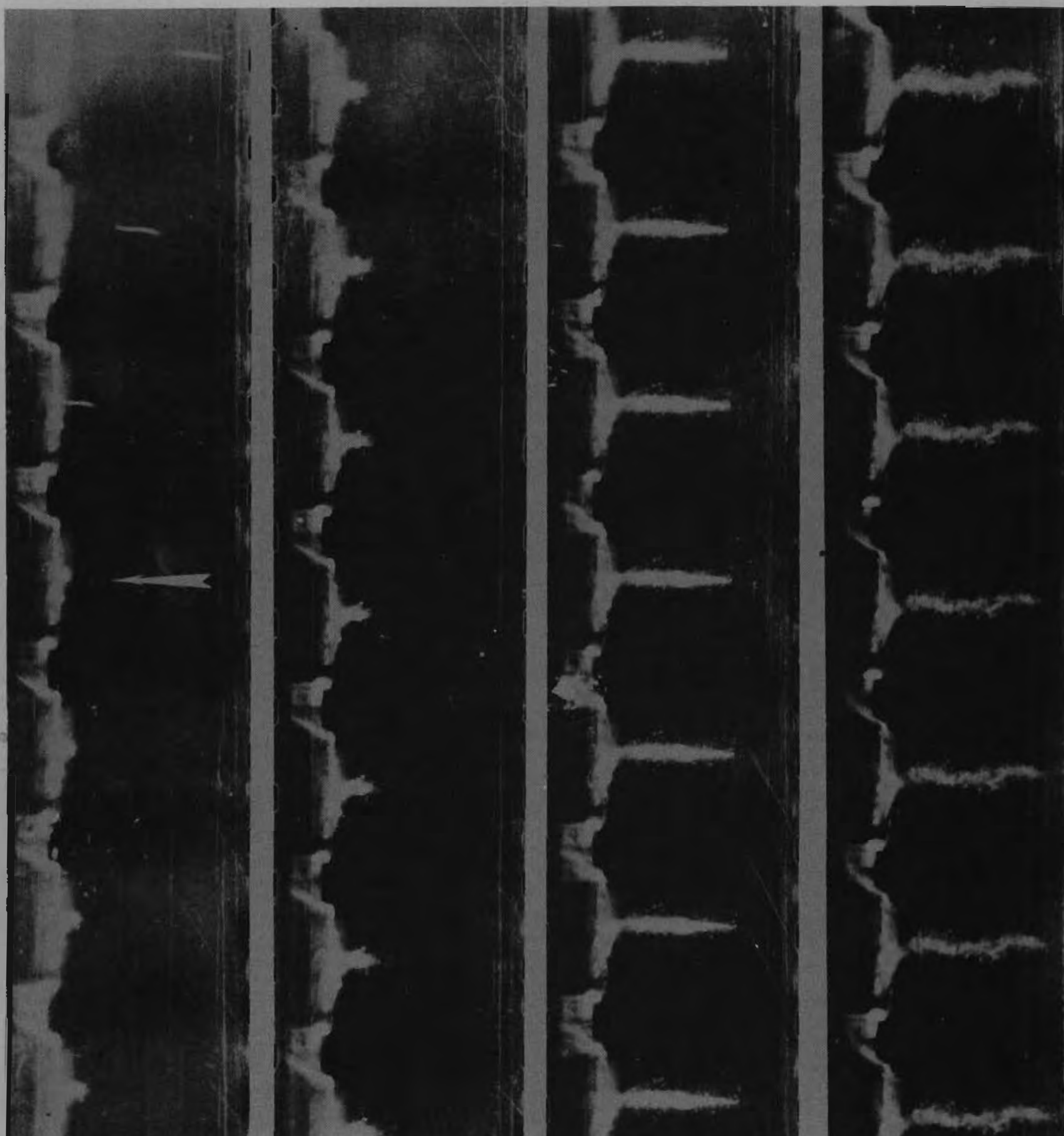


FIG. 30. Bullet Entry into Empty Goodrich Bomb Bay Cell. Strips 1,2: Point of impact through 3 milliseconds. Strip 3: Beginning at 12 milliseconds. Strip 4: Beginning at 40 milliseconds. Arrow denoted emergence of spray of tank fabric. Ammunition used: Cal. .50, Ball, at 175 yards.

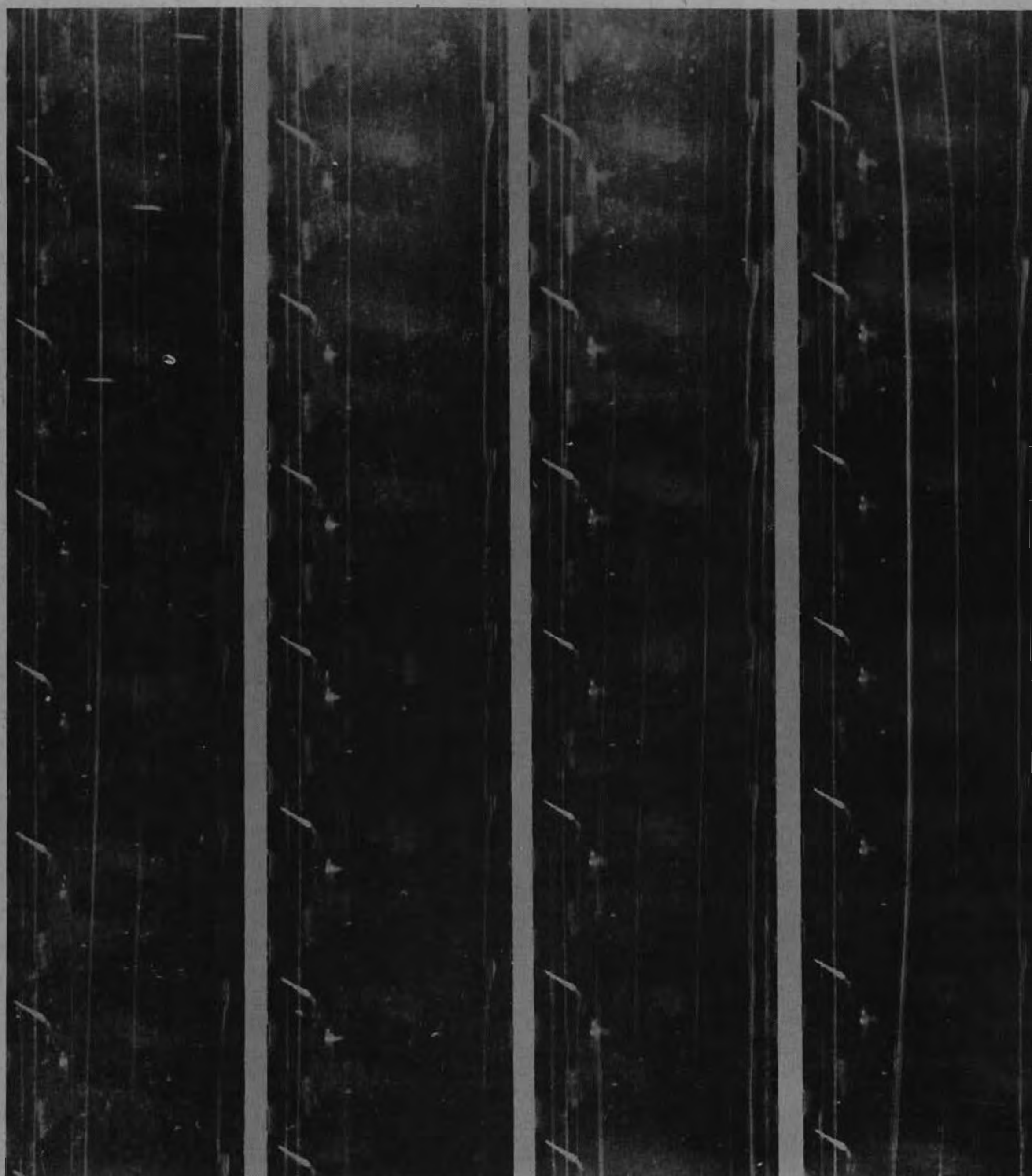


FIG. 31. Bullet Entry into Empty US Rubber Bomb Bay Cell. Strip 1: Shows point of impact. Strip 2: Begins at 2 milliseconds. Strip 3: Begins at 6 milliseconds. Strip 4: Begins at 17 milliseconds.

FIG. 32. Bullet Entry into a Heinkel Cell. Strip 1: Impact into empty cell and first millisecond. Strip 2: Begins milliseconds. Strip 3: Impact into full cell. Strip 4: Begins 6 milliseconds after impact into full cell. Arrow denotes emergence of spray from impact hole. Ammunition used: Cal. .50, Ball, at 175 yards.

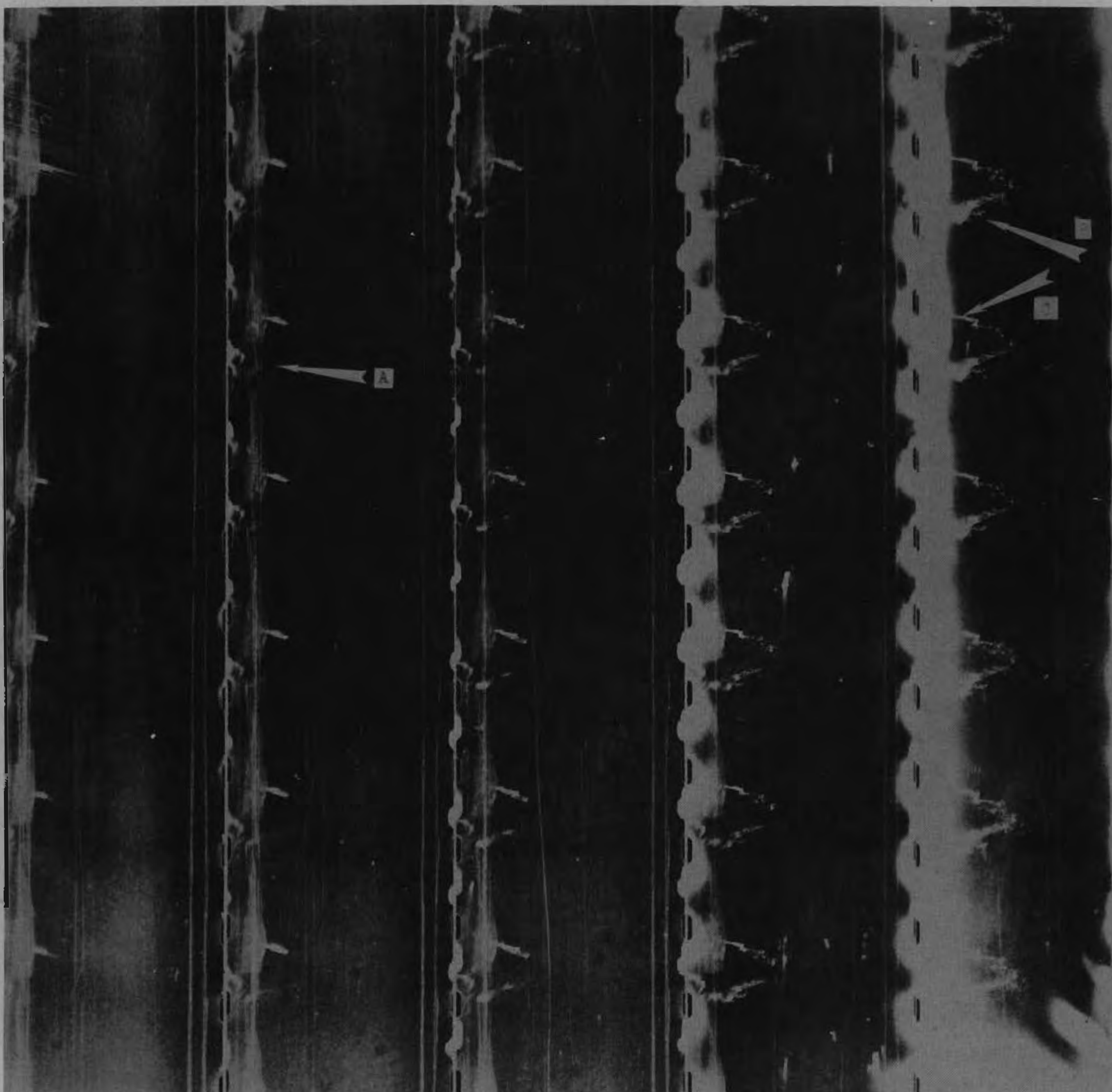


FIG. 33. Bullet Entry into Heinkel Cell. Strip 1: 12 milliseconds after impact into full cell. Strip 2: Begins at 24 milliseconds. Strip 5: Begins at 29 milliseconds. Arrow "A" denotes emergence of spray from filler cap. Arrow "B" shows later spray from filler cap. Arrow "C" denotes spray from point of impact.

100A damage resulted. In no case, however, was the weight of charge allowed to exceed the weight sufficient for a kill due to structural damage. At eight positions out of the twelve, approximately half the weight of charge required for "A" structural damage was sufficient for an "A" kill due to fuel cell fire. In the other 4 cases, no fires resulted from charges smaller than those required for structural kills. Tests with bare charges in a number of different positions on the outside of the wing skin are now in progress. These positions simulate those obtained with superquick fuze action on an HE shell.

STATIC DETONATION OF 20MM HEI, M97

In order to study the ability of a small caliber high-explosive incendiary shell to ignite a fuel cell, the 20mm HEI, M97 was statically detonated in various positions on the outside in the wall, and on the inside of gasoline-filled fuel cells. The shell was statically detonated since the M75 fuze gives erratic functioning and the position of functioning is important to fuel tank ignition. The results for this shell when fired at various ranges are presented in an earlier part of this report.

The results of the static detonations are shown in Figure 34. It is evident that the shell will ignite a gasoline-filled cell through but a small part of its path, namely where part of the shell is in the tank wall. The shell detonated in some positions outside the cell wall did not even result in leakage. Those inside the cell and adjacent to its wall caused leakage but no fire. One shell detonated in the center of a B-17 main tank did not cause any penetration of the tank wall. It is important to remember that kerosene-filled tanks will generally be more difficult to ignite than those filled with gasoline.

It is evident that proper fuzing is vital for a small caliber HEI shell. A fuze which shows promise of being developed to function in the wall of a fuel tank is the German hydrodynamic fuze, AZ-9501, which has been the subject of a careful study.[1]

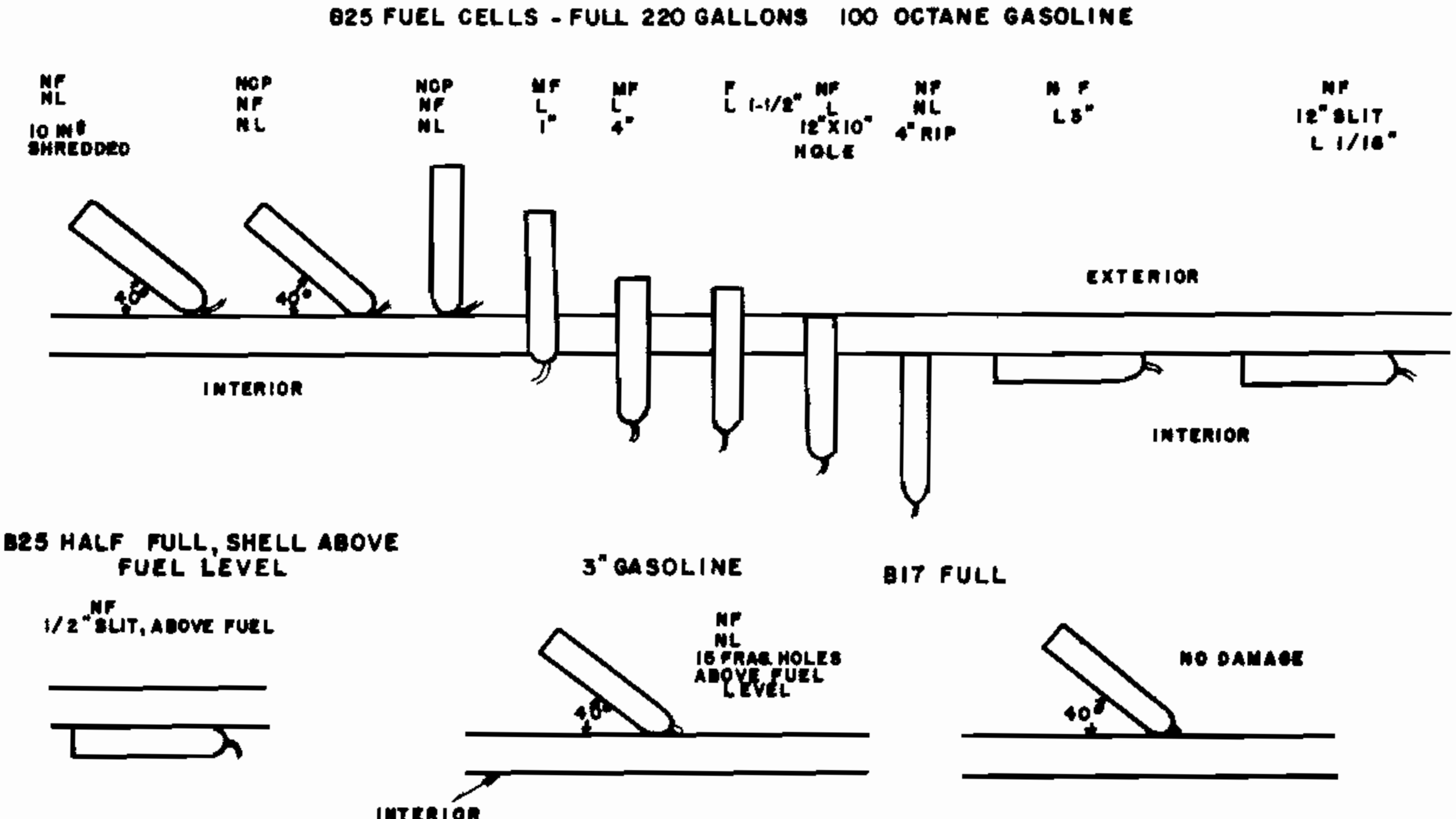
EFFECT OF HOLLOW CHARGES ON AIRCRAFT FUEL TANKS

Hollow charges of various sizes are being fired against B-17 wings with gasoline-loaded fuel cells and also against bare fuel cells. The object of the tests is to determine the effect of weight of explosive, type of liner and stand-off distance against various types of fuel tanks. Detailed analysis of results awaits the completion of the firings. An outline of results to date follows:

The U.S. Navy Cavity Charge Mk II was filled with 305 grains of 50/50 cast pentolite, with a 25 grain tetryl booster, drilled for Engineer's Special Blasting Cap. The charges were placed in contact with the exterior surface of the top and bottom skins and directed towards gasoline-loaded cells. Fifteen of the Mk II charges have been thus detonated at various positions on the B-17 wing. Of these fifteen, three resulted in small fires fed by leaking fuel, three in flash fires which extinguished themselves, 4 in non-self-sealing leaks and 5 in self-sealing leaks. This one inch diameter charge is of possible use as a daughter pellet from a missile warhead and will not be tested at long stand-off from wing skin.

[1] BRLM 479 (c) "Experimental Study and Appraisal of the German Hydrodynamic Fuze AZ-9501," by L. Zernow and J. M. Regan.

EFFECT OF 20MM HEI STATIC DETONATION AGAINST FUEL CELLS FROM TOP VIEW



CODE: F = FIRE, NF = NO FIRE
MF = MEDIUM FIRE

L = LEAKAGE
NL = NO LEAKAGE

CP = CELL PENETRATED
NCP = CELL NOT PENETRATED

FIG. 34

Proposals have been made for the inclusion of hollow charges in a small caliber projectile to fire back through the base after the projectile has penetrated into the fuel tank. The Mk II charge was detonated on the inside of the gasoline-filled fuel cells at stand-off distances from the tank wall of from 0" to 2". In each of four trials, large leakage resulted. However, the fuel was not ignited in any instance so that no improvement over the performance of bare TNT charges is evident with hollow charges of this size.

The U.S. Navy Cavity charge Mk I (.74 lbs of 50/50 Pentolite, 2-1/4" diameter) was also detonated within gasoline-filled fuel cells. These charges, at stand-off distances of 0" to 3" each resulted in large fires and complete destruction of the tank. Firings within tanks with intermediate charge diameters are planned.

The Mk I charge was also detonated at respective stand-off distances of 10 feet and 19 feet from bare gasoline-filled cells with large fire resulting at the closer distance and large non-self-sealing leakage resulting at both distances.

The U.S. Navy Cavity Charge Mk III (1.4 lbs 50/50 Pentolite, 3" diameter) was detonated 16 times against bare gasoline-filled self-sealing fuel tanks at stand-off distances of from 10 feet to 100 feet. Large fires were always obtained at distances up through 30 feet, and mixed results in the region from 35 feet through 60 feet. The detonation at 100 feet stand-off resulted in non-self-sealing leakage but no ignition. This same charge was detonated against gasoline-filled self-sealing fuel tanks with a sheet of .102" 24ST Dural placed 1 ft. in front of the tank and perpendicular to the line of fire. At distances of 60 ft., 75 ft., and 100 ft., there were obtained one, one and three large fires respectively out of the same number of charges detonated. At 150 feet, 2 small fires out of 5 charges were obtained and at 200 ft., the one round fired to date resulted in slight seepage of fuel, but no fire. Further firings with this charge are in process to determine the sensitivity curve for ignition. It is interesting to note that fires have been obtained at distances where the jet spray has diverged to about 2 feet in diameter.

Five rounds were also fired with the rocket warhead, M6A3 (bazooka, .5 lb. Pentolite, 2" diameter). Large fires were obtained up to 8 feet stand-off and no fires beyond that distance.

Firings are also contemplated with long stand-off distances for 15 and 40 lb. hollow charge warheads.

FUEL HOSE

In general, the fuel hose on the target aircraft has been easily ignited, especially when under pressure. This hose was of the self-sealing type but may have been especially vulnerable because of aging. It is understood that non-self-sealing hose is presently planned for new aircraft. A recommendation to this effect was made as a result of recent tests at Wright Field.[1] Arrangements have been completed for the procurement of sufficient lengths of new hose for tests at Aberdeen, of both self-sealing and non-self-sealing types.

[1] MCREXP-524-1829, Power Plant Laboratory, "Evaluation of Resistance of Aircraft Hose to High Caliber Gunfire," 24 February 1948.

STRATOSPHERE CHAMBER

Tests are planned to study ignition at high altitudes in a stratosphere chamber, available at Aberdeen, within which it is planned to conduct the tests at pressures down to about 1/10 of an atmosphere and temperature down to -55°C. In this chamber it will be possible to study fragment flash at high altitudes and the ignition of spray under laboratory conditions. The feasibility of conducting actual gunfire tests against gasoline filled tanks in the chamber is still under study.

ACKNOWLEDGMENT

This report was written under the general direction of Mr. H. K. Weiss. The firings were conducted by proof directors assigned to the Terminal Ballistics Branch of the Arms and Ammunition Division, Development and Proof Services. Assessments of damage were made by Air Force and Navy officers assigned to the Optimum Caliber Program. Mr. M. M. Lavin, Mr. C. J. Thomas, and Major R. I. Schnittke of CHORE assisted in the preparation of the fuel tank data on a working visit to the Ballistic Research Laboratories. The authors are indebted to Mr. Ed S. Smith for his constructive review.

Arthur Stein

Arthur Stein

Mary Gene Torsch

Mary Gene Torsch

APPENDIX A

THE MECHANISM OF FUEL TANK IGNITION BY INCENDIARIES*

The purpose of this section is to discuss the general problem of fuel tank ignition and to apply the data to the airborne aircraft. The term, "fuel tank ignition," includes both explosions and fires. Explosions occur if the ratio of fuel vapor to air is within certain limits, described later. Fires occur if that ratio is higher, up to a certain value.

The rounds discussed in the earlier parts of this report, pierced the fuel tanks both above and below the liquid surface of gasoline at an ambient temperature range of 32.9°F to 75.2°F. (Average monthly temperature of 53.83°F). In the case of kerosene, only full fuel tanks were used. The firings were made against the target on the ground. A simulated slip stream of approximately 80 miles per hour was produced by another aircraft. The damage was assessed as though the airplane were airborne. The results are recorded in Figures 2 to 25 in the first part of this report.

For the purpose of discussion this section is divided into two headings: I. Explosions and II. Fires.

I. Explosions. For an explosion to occur within a container, the concentration of fuel vapor and oxygen must lie within a definite range. A considerable amount of work has been done in this field with 100 octane (gasoline) AN-F-48A and JP-1 (kerosene) AN-F-32 fuels. The results have been summarized in Hq. AMC Wright-Patterson AFB Memo Report.[1]

In this section JP-2 (kerosene) AN-F-34 has been excluded since this fuel has been replaced by JP-3 (kerosene) AN-F-58 with characteristics somewhat similar to 100 octane gasoline. As yet no study has been made of vapor pressure versus temperature or of explosive mixtures with this fuel.

In Figure 35, a plot is given of the temperatures versus total pressure (altitude), for the two types of fuels, JP-1 kerosene and 100 octane gasoline, (dotted curves). The data were taken from AMC Memo Report.[2] These curves are envelopes of a large number of similar curves representing different samplings. Within each of the two envelopes was superimposed a curve of temperature versus pressure (solid curves). The data for JP-1 kerosene were taken from the AMC Memo Report.[2] The data for 100 octane gasoline were taken from Hq. AMC Wright-Patterson AFB Memo Report.[3]

[1] Hq AMC, Wright-Patterson AFB, Memo Report Serial No. TSEPP-144-1698, "Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," 13 Sept 1946.

[2] Hq AMC, Wright-Patterson AFB Memo Report Serial No. TSEAM-M5204, "Inflammability Range of J. P. Fuels Nos. PPF 45-6, PPF 45-7, PPF 45-25", 26 Aug 1946.

[3] Hq AMC, Wright-Patterson AFB Memo Report Serial No. Eng. 57-531-203, "Inflammability Range of Various Aircraft Engine Fuels," 21 May 1943.

*The evaluation of the vulnerability of fuel installations in different types of aircraft which have not been used in firing tests and with types of ammunition still in design stage requires an understanding of the mechanics of fuel tank ignition. This is especially true if the effects of altitude and temperature are to be properly included. A preliminary survey of the literature has been made by Dr. A. Christy, of Project CHORE, during a working visit to the Ballistic Research Laboratories and by C. F. L. Mohr, Major, USAF, assigned to the Optimum Caliber project. The results of this survey with joint comments by Dr. Christy and Major Mohr are presented.

The explosive mixtures for JP-1 kerosene (Figure 35) and for 100 octane gasoline (Figure 37) were obtained from unpublished vapor pressure curves of Materials Laboratory, Chemical Branch, Wright-Patterson AFB. At 14.7 pounds per sq. in. pressure, the composition of the explosive mixture for JP-1 kerosene is roughly between 2% (A) and 0.4% (B) by volume. The corresponding composition for 100 octane gasoline is 7% (C) and 2% (D) by volume.

It should be stressed that these curves of explosive mixtures were obtained in the laboratory under fixed and controlled conditions with a spark of a definite duration initiating the explosion. However, when incendiaries are used to initiate the explosion it was shown[1] that explosion occurs with considerably leaner mixtures than those indicated in the curves of Figure 35. Using Cal. 0.50 incendiaries with JP-1 kerosene vapor and air mixtures, explosions occur at sea level at temperatures as low as -20°F, whereas the curves of Figure 35 show that no explosions should occur at sea level below 96°F. The discrepancy of the lower limit for 100 octane gasoline is not as great.

In order to assess whether or not explosions may occur under combat conditions, the temperatures and total pressures of the fuels within the fuel tanks must be known. Tests were performed at Blythe Army Air Field[2] to determine the lag between ambient and fuel temperatures for several types of airborne aircraft. Two of these curves are reproduced here, Figure 36 for ascending B-24E aircraft and Figure 37 for P-38G. On these figures, altitude scales have been superimposed on the ambient temperature scales. Temperatures for various altitudes were obtained from the U. S. Department of Commerce Weather Bureau data.[3] For the closest approximation to Blythe Field the data for Phoenix, Arizona were taken.

In Figure 36 for the B-24E bomber, the ambient temperature dropped during climbing (approximately 32,000 ft) from 102°F to -25°F while the fuel temperature dropped from 110°F to 92°F. In Figure 37, for the P-38G interceptor, the ambient temperature dropped during climbing (approximately 32,000 ft.) in the first 29 minutes from 107°F to 14°F, while the fuel temperature dropped for the same period of time from 104° to 100°F. For the next forty-one minutes, while the aircraft was descending, the temperature rose from 14°F to 107°F. The fuel temperature continued to drop to 90°F. Both of these curves show the enormous temperature lags that may be encountered under flight conditions.

For the above case, there was no explosive mixture, as defined in Figure 35, within the gasoline tank, as far as the temperature effect of the mixture was concerned. Figure 35 shows the temperature of the explosive mixture range to be considerably above the fuel temperatures encountered. However, as it will be pointed out later, explosive mixtures were undoubtedly present in fuel tanks when the P-38 landed, due to the lag of equilibrium pressure within the tank. If kerosene were used as the fuel, explosive mixtures would have been encountered during the flight if the ground temperature were considerably below 0°F.

The results of the simulated flight patterns quoted,[4] show the effect of the non-equilibrium con-

[1] Hq AMC, Wright-Patterson AFB, Memo Report Serial No. TSEPP-144-1698, "Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," 13 Sept 1946.

[2] Hq AMC, Wright-Patterson AFB Memo Report Serial No. Eng. 57-525-149, "Desert Tests of the Power Plant Laboratory at the Blythe Army Air Field, Blythe, California," 18 Aug 1943

[3] U. S. Department Commerce Weather Bureau, Technical Note on Upper Air Maximum Temperatures at Standard Levels over U. S. and Alaska, Revision 1943.

[4] Hq AMC, Wright-Patterson AFB, Memo Report Serial No. TSEPP-144-1698, "Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," 13 Sept 1946.

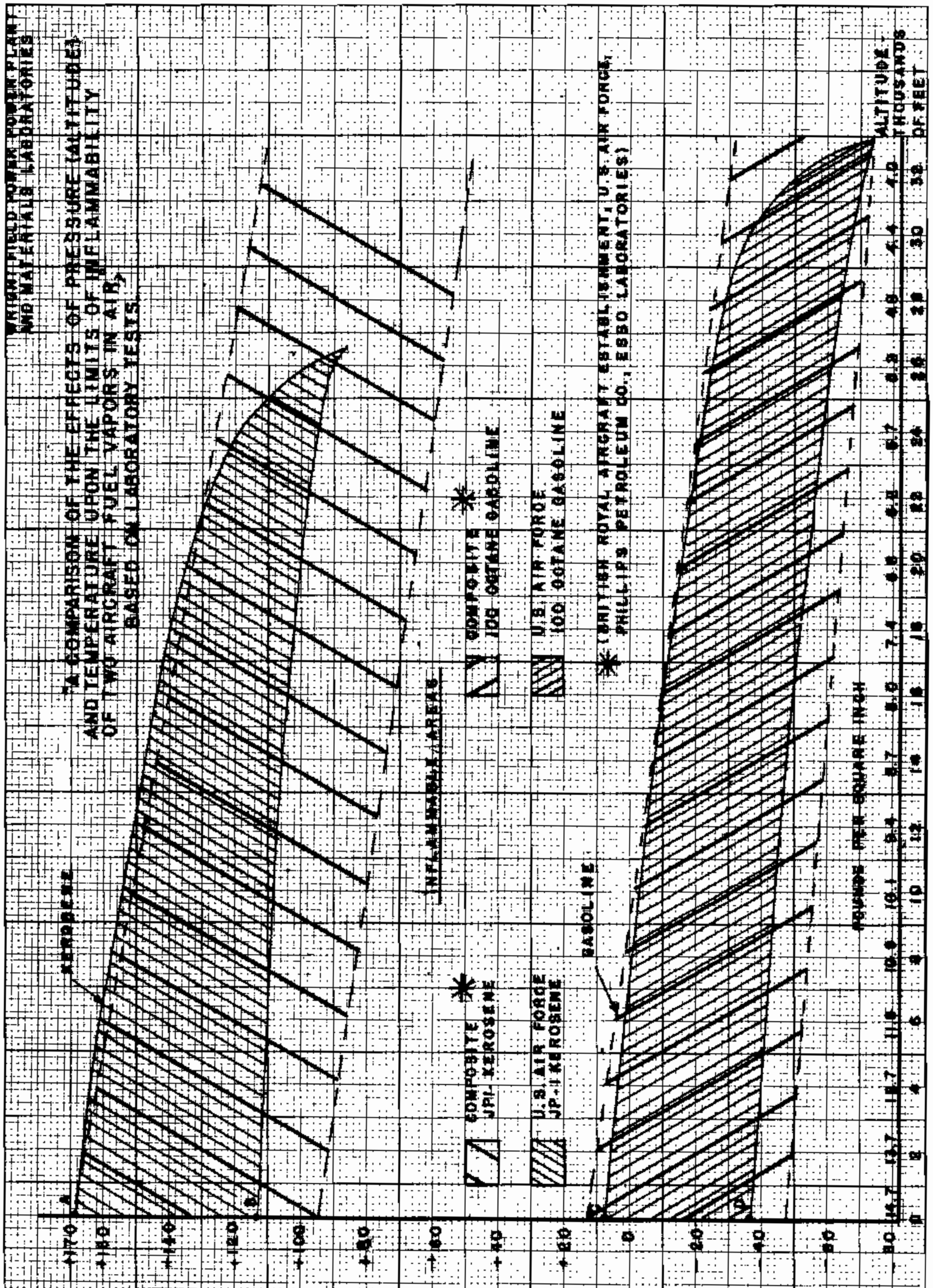
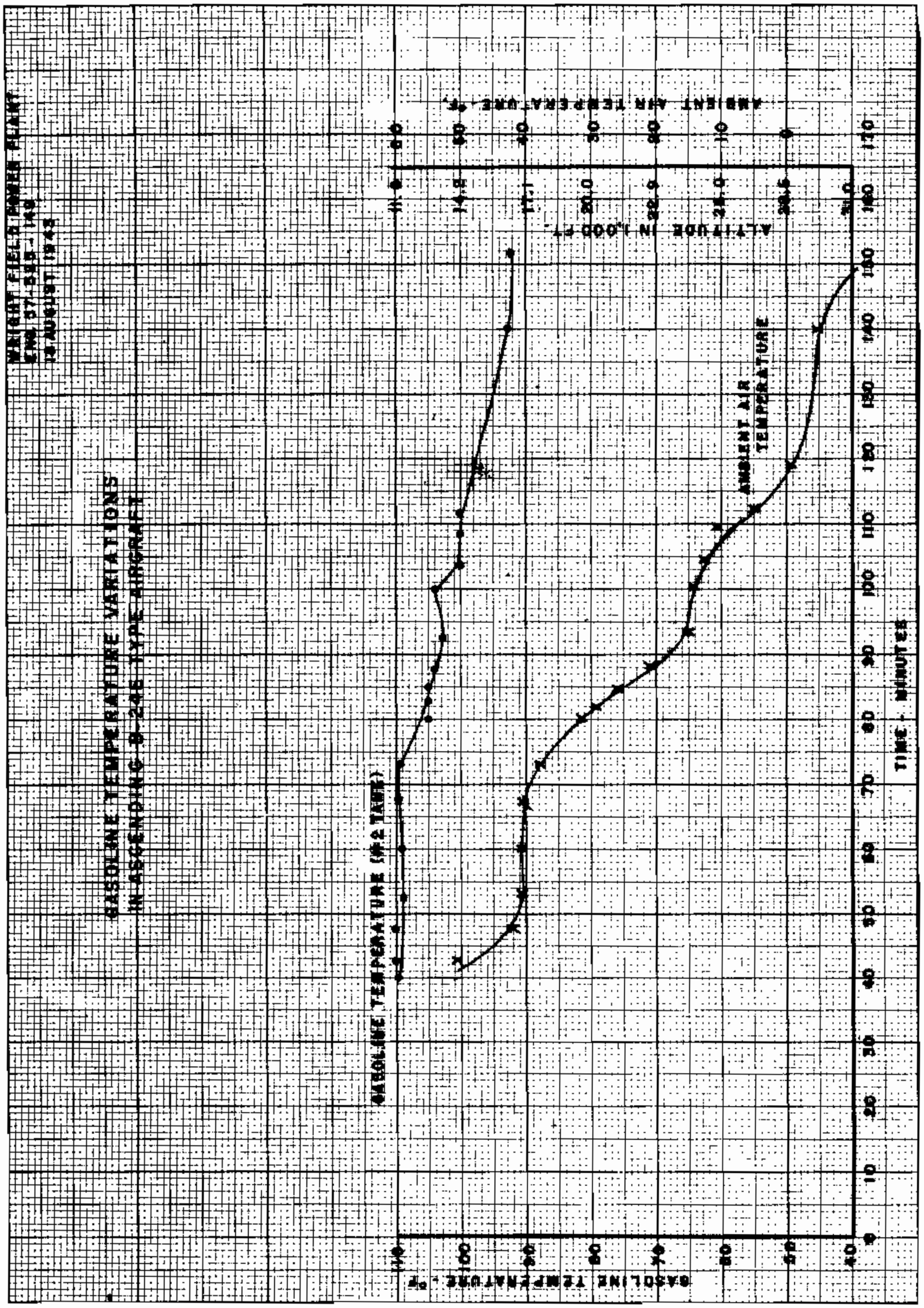

WRIGHT FIELD POWER POWER PLANT
AND MATERIALS LABORATORIES
"A COMPARISON OF THE EFFECTS OF PRESSURE (ALTITUDE)
AND TEMPERATURE UPON THE LIMITS OF INFLAMMABILITY
OF TWO AIRCRAFT FUEL VAPORS IN AIR,"
BASED ON LABORATORY TESTS.
KEROSENE
GASOLINE
INFLAMMABLE AREAS
COMPOSITE
JP1- KEROSENE
U.S. AIR FORCE
JP-1 KEROSENE
COMPOSITE
100 OCTANE GASOLINE
U.S. AIR FORCE
100 OCTANE GASOLINE
(BRITISH ROYAL AIRCRAFT ESTABLISHMENT, U.S. AIR FORCE,
PHILLIPS PETROLEUM CO., ESSO LABORATORIES)
TEMPERATURE - °F
+170
+160
+140
+120
+100
+80
+60
+40
+20
0
-20
-40
-60
-80
POUNDS PER SQUARE INCH
14.7
13.7
12.7
11.8
10.9
10.1
9.4
8.7
8.0
7.4
6.8
6.2
5.7
5.3
4.8
4.4
4.0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
ALTITUDE
THOUSANDS
OF FEET

FIG. 35



GASOLINE TEMPERATURE VARIATIONS
IN ASCENDING B-24E TYPE AIRCRAFT
GASOLINE TEMPERATURE (#2 TANK)
AMBIENT AIR TEMPERATURE
TIME - MINUTES
ALTITUDE IN 1,000 FT.
AMBIENT AIR TEMPERATURE - °F.
GASOLINE TEMPERATURE - °F

FIG. 36

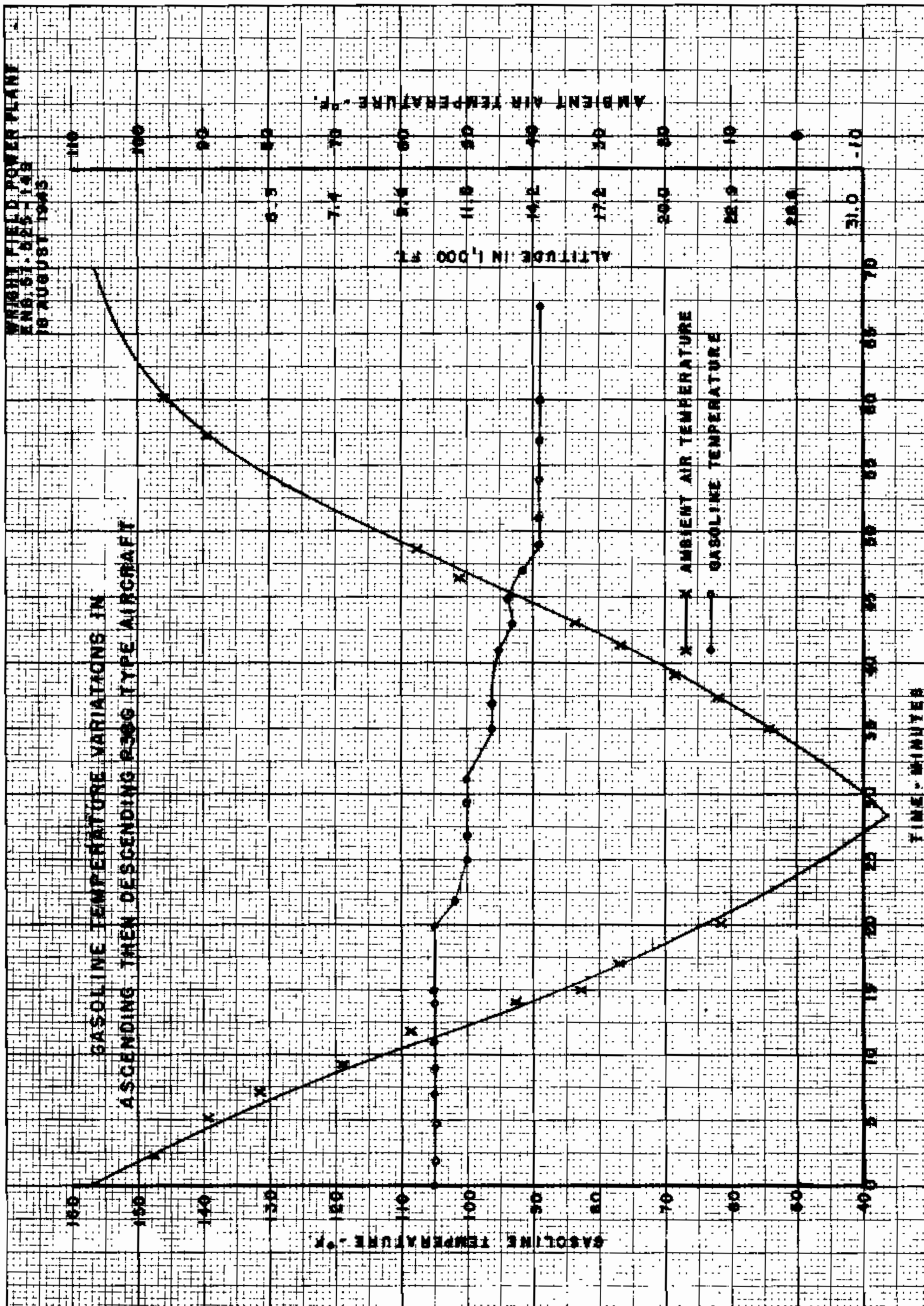

GASOLINE TEMPERATURE VARIATIONS IN
WRIGHT FIELD POWER PLANT
AMBIENT AIR TEMPERATURE - °F.
ALTITUDE IN 1,000 FT.
GASOLINE TEMPERATURE - °F
TIME - MINUTES
AMBIENT AIR TEMPERATURE
GASOLINE TEMPERATURE

FIG.37

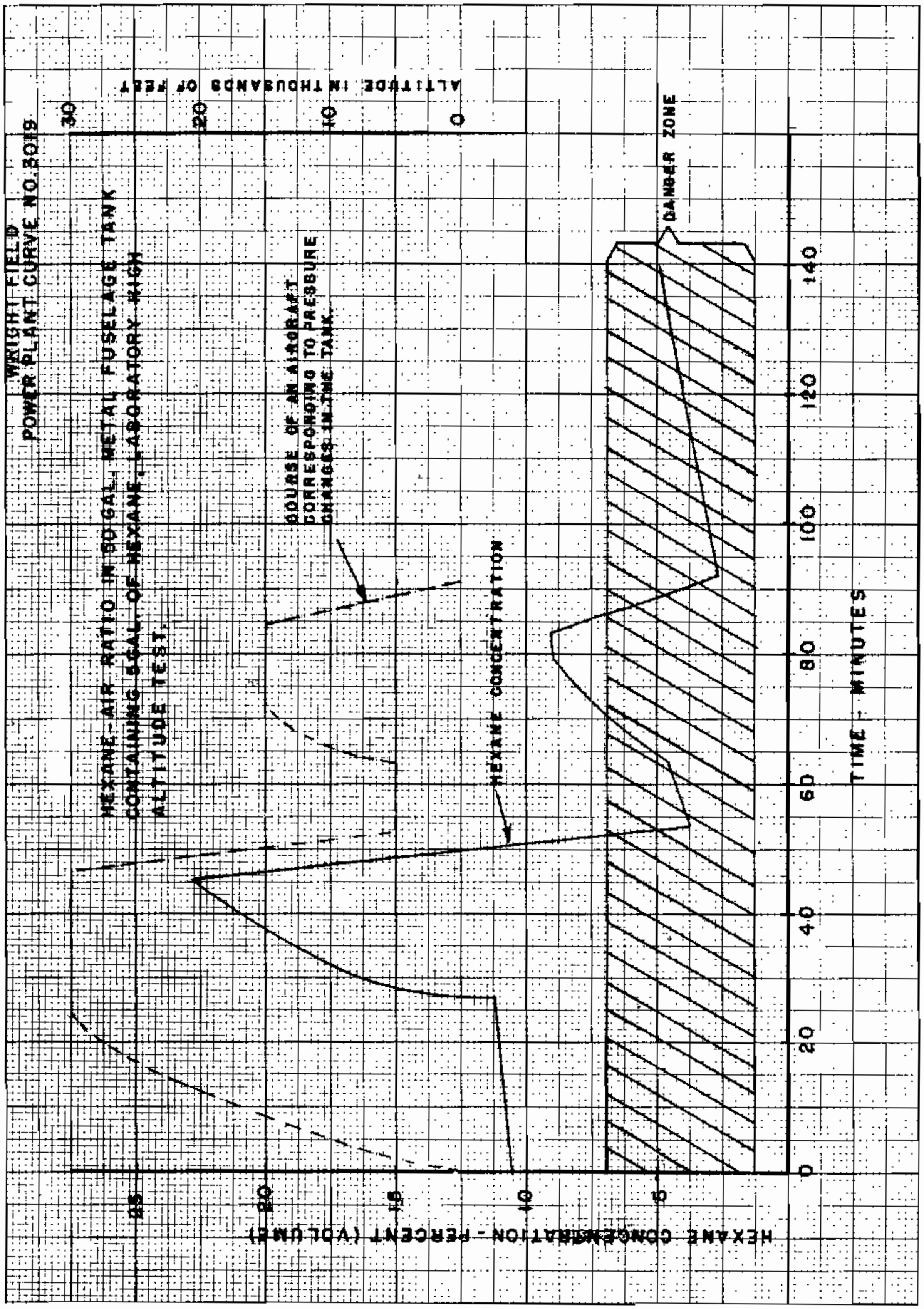

WRIGHT FIELD
POWER PLANT CURVE NO. 3019
HEXANE-AIR RATIO IN 50 GAL. METAL FUSELAGE TANK CONTAINING 5 GAL. OF HEXANE, LABORATORY HIGH ALTITUDE TEST.
COURSE OF AN AIRCRAFT CORRESPONDING TO PRESSURE CHANGES IN THE TANK.
HEXANE CONCENTRATION
DANGER ZONE
ALTITUDE IN THOUSANDS OF FEET
30
20
10
0
HEXANE CONCENTRATION - PERCENT (VOLUME)
25
20
15
10
5
TIME - MINUTES
0
20
40
60
80
100
120
140

FIG. 38

ditions within the tank during flight. The tank used was a 50 gallon metal fuselage tank of a Spitfire aircraft. Figure 38 is taken from reference (3). In this flight, hexane was used as a fuel for experimental purposes. However, gasoline would have shown very similar results. This figure shows that when the aircraft descended from 30,000 feet to the ground, an explosive mixture of hexane and air remained in the tank for over 80 minutes after landing. On climbing, air and hexane vapors are removed from the tank through the vent. This increases the hexane-to-air ratio and results in a mixture too rich for an explosion. On descending, air enters the tank through the vent. Conversely this decreases the hexane-to-air ratio and results in an explosive mixture. The curve shows that, possibly due to the small size of the vent, equilibrium conditions are not reached even after 80 minutes.

In summary, factors relating to the probability of an explosion besides the experimental laboratory data are:

1. Results of incendiary firings.
2. Temperature lags encountered in actual flight.
3. Non-equilibrium conditions encountered in actual flight.

Each of these three factors indicates that the explosive limits of JP-1 kerosene and 100 octane gasoline are considerably larger than those obtained from the laboratory data.

The probability of a structural kill is a function of the size of the tank and the amount of vapor present. An explosion need not cause a structural kill directly but may cause fires or even a pilot kill, due to gasoline seepage or any of numerous other factors.

Considerable research has been conducted on the problem of purging fuel tanks, i.e., replacing air with non-combustible gases.[1, 2] From the above discussions it appears that purging will be especially necessary if kerosene is used and it would be very desirable with gasoline. It should be noted that, since the beginning of World War II, purging was used by the Russians. The climatic conditions encountered by them made it necessary.

II. Fires. As discussed above, a richer fuel vapor-air mixture is required for fires than for explosions. No experimental data are as yet available for the upper limit of the fuel vapor to air ratio which may be applicable to an airborne aircraft.

If an incendiary round enters the tank above the liquid level and functions in an inflammable mixture the vapor will burn and either of two things will happen:

1. If the opening caused by the round is small, a low-order explosion may occur by the expansion of the resulting gases. The fire may extinguish itself due to lack of oxygen and no serious damage to the structure will result.

2. If the opening is large enough, air can enter to support combustion and a fire may result which may cause a kill.

If a round enters below the liquid level, fire may result in several ways. Due to the complexity of structure in an aircraft, fires may result in numerous ways either from a direct hit of the fuel tank by

[1] Hq AMC, Wright-Patterson AFB, Memo Report Serial No. TSEPP-144-1698, "Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," 13 Sept 1946.

[2] U. S. Deptartment of Interior, Bureau of Mines R13871, "Extinction of Gasoline Flames by Inert Gases," April 1946.

incendiaries or by subsequent rounds igniting the fuel which may have leaked out due to a previous hit. Fires may be caused either directly from the burning incendiary material or indirectly by metal particles which have been heated by the incendiary material.

It has been shown that, with a self-sealing rubber aircraft fuel tank, it may require about 7 milliseconds for the spray to come out after the round pierces the tank; therefore, the duration of the incendiary flash, after the round pierces the tank, must be greater than 7 milliseconds. There are other conditions, however, that have to be met before a fire occurs. The incendiary is actuated after it pierces the metal skin of the airplane. Values are given in other parts of this report of the duration, length of flash and distance of the heart of the fire from the metal plate which causes the incendiary to function. Hence, in order for fire to occur due to a direct hit by an incendiary, there must be space between the actuating skin and the rubber tank.

It is obvious that, if the self-sealing tank were adjacent to the metal skin, there would be small probability of fire caused by any one round entering the skin at zero obliquity.

On the other hand, the probability of the tank not sealing for this particular case would be greater, since, due to the petalling effect, the edges of the metal skin may prevent the tank from being self-sealing. Thus for this case, the probability of fire caused by a subsequent round in that neighborhood will increase. One may expect that, for any one type and caliber of incendiary projectile, at zero obliquity, the probability of fire may be maximum at some particular spacing between metal skin and tank. It is questionable, however, whether this spacing will be the same at other obliquities. The complexity of the effects is such that it is questionable whether much will be gained if an attempt is made to separate the effect of direct and compound hits.

It has been observed that a fire, whose source is exposed to the slip stream, is extinguished if the speed of the aircraft exceeds 110 miles per hour.[1] In the tests which have been conducted, smoke was observed while the slave ship was producing a slip stream against the target. Flames were evident only after the engines of the slave ship were stopped. It seems that an effective kill can only be produced by fires whose source is protected from the air currents of the slip stream.

As was earlier noted, the ratio of fuel vapor to air is smaller for an explosive mixture than for an inflammable mixture. Also, one may expect that, as the altitude is increased, the ratio of probability of fire to explosion will increase. At very high altitudes, however, both of these probabilities may be very small due to lack of enough oxygen to support either fire or explosion. Tests conducted by the Ordnance Department have indicated no significant difference in ignition of Heinkel replica tanks between sea level and 20,000 feet.[2, 3]

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[1] Hq AMC, Wright-Patterson AFB, Memo Report Serial No. TSEPP-144-1698, "Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," 13 Sept 1946.

[2] First Report on Altitude Tests of Cartridge, Incendiary, Caliber .50, M1 and Cartridge, Armor Piercing – Incendiary, Caliber .50, M8, OP No. 5374, December 1943 (C).

[3] Second Report on Altitude Tests of Cartridge, Incendiary, Caliber .50, M1, and Cartridge, Armor Piercing – Incendiary, Caliber .50, M8, OP No. 5374, Project 2664, May 1944 (C).

Tests will be initiated in the very near future with a closed chamber and a stratosphere chamber to determine such probabilities. At the projected high altitudes which are contemplated for future aircraft, this effect of altitude will be extremely important, for it may well be that the probabilities are so small as to make this mode of attack impracticable.

Let

$P = p_A + p_F$, where

P = total pressure,

p_A = pressure of air, and

p_F = fuel vapor pressure, a function of temperature.

Also $\frac{p_F}{p_A}$ is proportional to the fuel to air ratio discussed above and is an inverse function of P. Therefore, at some low total pressure P and corresponding high altitude, the fuel-to-air ratio will be too large for either explosions or fires. Unfortunately, no laboratory data are available on the dependence of the above ratio on temperature and total pressure. Hence, no calculations can be made to determine the minimum altitude above which no fires or explosions will occur.

APPENDIX B

FUEL TANK SURVIVAL PROBABILITY FOR "n" HITS

The figures presented in this report enable one to compute the probability that an aircraft sustaining "n" hits will survive fuel tank damage. A formula for the total probability of a kill due to fuel tank fire in "n" hits on any aircraft, including both single-shot and compound fires was developed in a previous report.[1] The development is used here because of its direct connection with the purpose of this report.

The formula (on Page 4 of this report) for the single-shot probability of an "A" kill due to fuel tank fire may be used for each of the separate fuel tank locations on the plane. The product of the single-shot survival probabilities for each fuel tank location will then be the single-shot survival probability for all the areas combined. This may be denoted by $1 - P^{(1)}_{A_{F_{ss}}}$. The probability of an "A" kill due to single-shot fuel damage in "n" hits is then

$$P^{(n)}_{A_{F_{ss}}} = 1 - (1 - P^{(1)}_{A_{F_{ss}}})^n$$

There is an additional source of fuel tank fire damage due to the additional probability that a round may cause a fire when a previous round impacting in the same general area has caused leakage. This is a form of non-commutative compound damage as distinguished from the commutative compound damage one attains with doubly vulnerable components such as engines or pilots on a multi-engined bomber. This type of fuel tank damage is especially important when there is more than one burst on the target. Let P_{F_c} be the compound probability of a fire for a functioning penetration on a leaking cell. P_{F_c}, which would be written as ($P\ F_c$/fcn, CP) in the formula on Page 4 may be estimated for gasoline or kerosene from Figures 10 and 11, respectively. $P_{F_{ss}}$ is the single-shot probability of a fire for a functioning penetration of an undamaged cell. $P_{F_{ss}}$ would be written as ($P\ F_{ss}$/fcn, CP) in the formula for P_{A_F} and its value may be estimated for gasoline or kerosene from Figures 8 and 9, respectively.

Let $P_{F_{\Delta c}} = P_{F_c} - P_{F_{ss}}$ be the additional probability of a fire due to previous leakage and $P_{L_{ss}}$ be the probability of leakage and no fire for a single-shot hit on the target cell. $P_{L_{ss}}$ may be estimated from Table I. Then

$$P_{F_m} = 1 + \frac{P_{F_{\Delta c}} (1 - P_{L_{ss}})^m - P_{L_{ss}} (1 - P_{F_{\Delta c}})^m}{P_{L_{ss}} - P_{F_{\Delta c}}}$$

is the probability of getting at least one fire due to compounding of damage if the cell is hit "m" times. The

[1] BRLM 437 "Optimum Caliber Program" by A. Stein.

probability of getting "m" hits on the cell out of "n" rounds can be calculated separately for each fuel tank area. Thus, for the near main cell (denoted by NM), this probability is

$$\frac{e^{-np_{NM}} (np_{NM})^m}{m!} ,$$

using the Poisson approximation to the binomial.

Then for any one fuel tank location, say for the near main cell, the probability of fire, due to compounding, for "n" hits on the plane is

$$P_{CF}^{(n)} = \sum_{m=o}^{m=n} \frac{e^{-np_{NM}} (np_{NM})^m}{m!} P_{F_m}$$

If $(P\ A/F_c)$ is the probability of an "A" kill on the plane due to compound fire (See Table I, parts C and D), then

$$P_{A_{F_c}}^{(n)} (NM) = (P\ A/F_c)\ P_{CF}^{(n)}$$

is the probability that "n" hits on the plane will result in an "A" kill due to the additional probability of compound fires in the near main cell.

For example, if the far main cell is the only other cell containing fuel when the plane is over the target, then

$$P_{A_F}^{(n)} = 1 - (1 - P_{A_{F_{ss}}}^{(n)}) (1 - P_{A_{F_c}}^{(n)} (NM)) (1 - P_{A_{F_c}}^{(n)} (FM))$$

is the total probability of an "A" kill due to fuel tank fires in "n" hits on the plane, including both single-shot and compound fires.

An indication of the effect of compound fuel damage may be obtained from calculations made for the B-25 target in a previous report.[1] It appears from these calculations that the effect of compound damage is appreciable only where the single-shot probability is itself extremely small. From a consideration of data accumulated to date, therefore, there would seem to be but little difference in overall aircraft vulnerability for widely varying time intervals between impacts. If this is so, then from the terminal ballistic standpoint, the vulnerability of the target under repeated passes would be little different from that for one long burst with the same number of hits. The application of this fact will simplify calculations of the outcome of aircraft duels.

[1] BRLM 462 "Airplane Vulnerability and Overall Armament Effectiveness", K. H. Weiss and A. Stein, pages 46-49.

APPENDIX C

BIBLIOGRAPHY

"Annual Report of Research and Technologic Work on Explosives, Explosions, and Flames," Bureau of Mines RI 4176, Bernard Lewis, Dec 1947.

"Application of the Technique of High Speed Radiography to the Study of Armor Penetration of 20mm AP Shop-Preliminary Investigation, FA R-807," Confidential, H. E. Satzinger and E. R. Thilo.

"Aviation Fuels and Their Effects on Engine Performance" Formerly T0-06-5-4, Restricted, Not now published, U. S. Air Force purchase order 33-038 44-5908-E.

"Airplane Vulnerability and Overall Armament Effectiveness," Ord Dept BRL, Aberdeen Proving Ground, Maryland. Memo Report No. 462, Confidential, Herbert K. Weiss and Arthur Stein, 21 May 1947.

"Calculation of the Effect of 88mm Shell on Aircraft," N. F. Mott German AORG Memo No. 68.

"Desert Tests of the Power Plant Laboratory at the Blythe Army Air Field, Blythe, California," Hq. AMC Wright-Patterson AFB Memo Report, Serial No. Eng. 57-525-149, 18 August 1943.

"The Effect of Blast on Aircraft, Reciprocating Engines," Ord Dept. BRL, Aberdeen Proving Ground, Md. Memo Report No. 467, Confidential, Arthur Stein and Harry Kostiak, 28 August 1947.

"Experimental Study and Appraisal of the German Hydrodynamic Fuze AZ-9501," BRL Memo Report M479 Confidential, Louis Zernow and Joseph M. Regan.

"Explosion and Combustion Processes in Gases," by Wilhelm Jost, translated by Huber O. Croft, McGraw-Hill, N.Y., 1946.

"The Explosive Range of Aqueous Solutions of Specially Denatured Alcohol," Hq AMC Wright-Patterson AFB Memo Report Serial No. TSEPP-539-2, 2 Sept 1947.

"Extinction of Gasoline Flames by Inert Gases," Bureau of Mines RI3871, G. W. Jones and W. H. Gilliland, April 1946.

"First report on the Ingition of Petrol - Vapour/Air Mixture by High-Velocity Projectiles and Fragments Ignition by Means of High Temperature Associated with the Bow-Wave," - Road Research Laboratory RRL Note No. MAP/57/ACW, WCM, ACL.

"Flame Propagation, Critical Review of Existing Theories," Mark Stein and Polamyi - Cornell Aero Lab, Bumble Bee Report B61, April 1947.

"Flight Tests on Fuel Transfer System on B24G Airplane Serial No. 42-78155," Hq. AMC Wright-Patterson, AFB Memo Report Serial No. TSEPL5-524-1605, 24 Sept 1945.

"Flight Variables Affecting Fuel Vapor Loss From a Fuel Tank," Charles Stone, NACA, E 186, Formerly MR No. E4L28, Sol Baker, Dugald O. Black, Dec 1944.

"Gunfire Tests to Determine the Vulnerability of Jet Propelled Aircraft Fuels," TED NPG 2599, U. S. Naval Proving Ground, Dahlgren, Va., Nov 1945, Dec 1945.

"Handling Aircraft Engine Fuel," Hq. AAF, Washington, D. C., AAF Manual No. 38-66-1, Feb 1944.

"Ignition of Fuel Tanks, - Attack from Above and Below," Royal Aircraft Establishment Farnborough. Hants Orfordness Research Station, F.T.-363, British Restricted, E. A. Hotham, Oct 1946.

"Ignition Range of Diesel Engine Fuel," Hq. AMC Wright-Patterson AFB Memo Report, Serial No. Exp-M-57-531-160, 23 Nov 1942.

"Inflammability of Gasoline Vapor-Air Mixtures at Low Pressures," Bureau of Mines RI 3966, G. W. Jones and I. Spolan, Oct 1946.

"Inflammability Range of Various Aircraft Engine Fuels," Hq. AMC Eng. Div., Wright-Patterson AFB Memo Report, Serial No. Eng. 57-531-203, Restricted, 21 May 1943.

"Inflammability Range of J. P. Fuels Nos. PPF 45-6, PPF 45-7 and PPF 45-25," Hq. AMC Wright-Patterson AFB Memo Report, Serial No. TSEAM-M5204, 26 Aug 1946.

"Inflammability Characteristics of Some Liquids," Hq. AMC Wright-Patterson AFB Memo Report, Serial No. EXP M-56-3486, 10 May 1941.

BIBLIOGRAPHY (Continued)

"Internal Exhaust Gas Purging System For Fuel Tanks in the B-17F Airplane," Hq. AMC Eng. Div, Wright-Patterson AFB Memo Report Serial No. Eng. 57-524-1085, 11 May 1944.

"An Investigation of Transient Pressures Produced in Fuel Cells by High Velocity Projectiles," Goodyear Fire and Rubber Co., Akron, Ohio, Stambough and Ostrowski, 1 Aug 1947.

"Minimum Spontaneous Ignition Temperature of Used Aircraft Engine Oils," Hq. AMC Wright-Patterson AFB Memo Report Serial No. EXP-M56-3486, Add. I, 9 July 1942.

"Motion Pictures, Tank Ignition Cal. .50 INC, M1 (3) 3-G-4-8," APG Firing Records: S-39192, S-42579 and S-47793.

"Note on the Damage Effect of Shell Fragments Against Self-Sealing Tanks," RAE, SME 156, Bird, June 1943.

"Note on the Vulnerability of Various Aircraft Fuel and Oil Systems to Enemy Action Damage," Operational Research Section (B.C.) Report No. 57, 29 Sept 1942.

"Optimum Caliber Program," Ord Dept BRL, Aberdeen Proving Ground, Maryland. Memo Report No. 437, Confidential, Arthur Stein, 1 July 1946.

"Passive Defense Measures for Personnel and Vital Installations in Aircraft. Hot Slosh and Gunfire Tests of One B-29 Non-Metallic Self-Sealing Bomb Bay Fuel Tank Submitted by U. S. Rubber Co.," Hq. AMC Eng Div, Wright-Patterson AFB Memo Report Serial No. TSEPP 524-1634, 24 Jan 1946.

"Passive Defense Measures for Personnel and Vital Installations in Aircraft. Hot Slosh and Gunfire Tests of One P-80 Self-Sealing Fuselage Fuel Tank Installation, B. F. Goodrich Co.," Hq. AMC Eng Div, Wright-Patterson AFB Memo Report Serial No. TSEPL-5-524-1480, 15 May 1945.

"Passive Defense Measures for Personnel and Vital Installations in Aircraft. Gunfire Tests of Two B-36 Wing Tanks, Consolidated Vultee Aircraft Corp.," Hq. AMC Eng Div, Wright-Patterson AFB Memo Report Serial No. Eng. 57-524-1198, Restricted, 22 July 1944.

"Penetration of Fuel Tanks by Projectiles, I. Formation and Ignition of Liquid Sprays," Ministry of Supply, Advisory Council on Scientific Research and Technical Development, Incendiary Projectiles Committee, Photographic Panel, Safety in Mines Research Station, Buxton A.C. 7290, H. C. Grimshaw, 9 April 1945.

"Penetration of Fuel Tanks by Projectiles, II. Formation of Liquid Sprays. Snapshot Photography," Ministry of Supply, Advisory Council on Scientific Research and Technical Development, Incendiary Projectiles Committee, Photographic Panel, Safety in Mines Research Station, Buxton AC 7863, W. C. F. Shepherd and V. O. Hardy, 9 April 1945.

"Penetration of Fuel Tanks by Projectiles, III. Formation of Liquid Sprays from Experimental Tanks," Ministry of Supply, Advisory Council on Scientific Research and Technical Development, Incendiary Projectiles Committee, Photographic Panel, Safety in Mines Research Station, Buxton AC 7865, W. C. F. Shepherd and V. O. Hardy, 9 April 1945.

"Penetration of Fuel Tanks by Projectiles, IV. Characteristics of the Sprays Produced by 0.303 In. Bullets in Stable Flight," Ministry of Supply, Advisory Council on Scientific Research and Technical Development, Incendiary Projectiles Committee, Photographic Panel, Explosives Research Committee (Physics and Physical Chemistry), Safety in Mines Research Station, Buxton E 153, W. C. F. Shepherd and V. O. Hardy, June 1945.

"Penetration of Fuel Tanks by Projectiles, V. Liquid Motion Set up by 0.303 In. Bullets Fired Downwards into Fuel Tanks," Ministry of Supply, Advisory Council on Scientific Research and Technical Development Incendiary Projectiles Committee, Photographic Panel, Explosives Research Committee (Physics and Physical Chemistry), Safety in Mines Research Station, Buxton E 155, W. C. F. Shepherd and V. O. Hardy, June 1945.

"Phillip Hydrocarbons," Chemical Products Dept., Bartlesville, Oklahoma.

"Report on the Probable Frequency and the Danger of Explosive Mixtures in Fuel Tanks during Operational Flying," RAE Report No. Ch333, W. G. Glendinning and W. G. Parker.

Royal Aircraft Establishment, Farnborough, Hants, Orfordness Research Station), Report No. Ch 325.

"Self-Sealing Protective Material for Gasoline Tanks Developed by Charles Vallogia," Military Attache, Paris R 655, 1946.

BIBLIOGRAPHY (Continued)

S.A.E. Paper "Some Economic Aspects of Aviation Fuel Volatility," Phillips Petroleum Co., W. D. Parker and R. C. Alden.

"Standard Atmosphere - Tables and Data," National Advisory Committee for Aeronautics Report No. 218, U. S. Government Printing Office, Walter S. Diehl, 1942. Reprint Oct 1925.

"Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," Hq AMC Wright-Patterson AFB Memo Report Serial No. TSEPP-144-1698, 13 Sept 1946.

"Summary of Data on Fires and Explosions in Combat Aircraft Fuel Tanks," Hq. AMC Wright-Patterson AFB Memo Report Serial No. TSEPP-524-1698, Add. 1, 8 Mar 1948.

"Technical Note on Upper Air Maximum Temperatures at Standard Levels over U. S. and Alaska", U. S. Dept. of Commerce, Weather Bureau, Revised 1943.

Tentative Tables for the Properties of the Upper Atmosphere, National Advisory Committee for Aeronautics, Jan 1947.

"Ventilation Involved in the Use of Gasoline Powered Equipment in Enclosed Spaces (not in Mines or Tunnels)," IC 7404, Bureau of Mines, L. B. Berger, June 1947.

"X-Ray Pictures of Current Production Caliber .30 M1 Incendiary Bullets During Performance Tests," FA T2161, E. R. Thilo.

"X-Ray Pictures of Current Production Caliber 0.50 M1 Incendiary Bullets During Performance Tests, First Report," FAR-321, E. R. Thilo.

"High Speed Motion Picture Study of Ignition of German Type Self-Sealing Tanks Placed to Rear of Heinkel Replica Target," FA 567, E. R. Thilo.

Record of Army Ordnance Research and Development, Volume 2, Small Arms and Small Arms Ammunition, Book 2, Small Arms Ammunition (C).

"Altitude Tests of Cartridge, Incendiary, Caliber .50, M1 and Cartridge, Armor Piercing-Incendiary, Caliber .50, M8, OP No. 5374 (First Report Dec 1943, Second Report May 1944) (C).

"Evaluation of Resistance of Aircraft Hose to High Caliber Gunfire," Hq. AMC, Eng. Div., Wright-Patterson AFB Memo Report, Serial No. MCREXP-524-1829, Restricted, 24 February 1948.

APPENDIX D

FUEL CELL FIRINGS SUMMARIZED - 1 MAY 1948

	Gasoline Firing Record No.	Total Hits on Projected Area* Single Shot	Com-pound	Kerosene Firing Record No.	Total Hits on Projected Area* Single Shot	Com-pound
B-25						
200 yards Rear Above						
3 cm AZ	P41071	2	2			
500 yards Rear and Above						
Cal. .50, API-T, M20	P41050					
Cal. .50, API-T, M20	P40496	37	13			
Cal. .60, API, T39	P41051					
Cal. .60, API, T39	P40497	15	10			
Cal. .60, Inc, T36E2	P40498					
Cal. .60, Inc, T36E2	P41053	8	15			
Cal. .60, Inc, T36E2	P41054					
20mm, HEI, M97	P41055					
20mm, HEI, M97	P41056	6	3			
20mm, Inc, M96	P41070					
20mm, Inc, M96	P41073	5	16			
37mm, HE, M54	P41072	4	0			
P-38						
54 yards Front Below						
Cal. .50, API-T, M20	P42299			P42317		
Cal. .50, API-T, M20	P42302	12	14	P42314	15	14
Cal. .50, API-T, M20	P42307			P42310		
20mm, Inc, M96	P42374			P42363		
20mm, Inc, M96	P42371	18	7	P42362	16	0
20mm, Inc, M96	P42377			P42352		
100 yards Rear Above						
75mm, HE, M48				P41289	4	0
105mm, HE, M1				P41464	3	0
200 yards Rear Above						
3 cm, HE, Mk 108	P41237	10	1	P41270		
3 cm, HE, Mk 108	P41256	5	1	P41663	14	11
500 yards Front Below						
Cal. .50, Inc, M23	P41626			P41486		
Cal. .50, Inc, M23	P41623	12	11	P41485	10	16
Cal. .60, API, T39	P41277			P41652		
Cal. .60, API, T39	P41276	12	14	P41649	11	25
Cal. .60, API, T39	P42122					
Cal. .60, Inc, T36E2	P41632			P41656		
Cal. .60, Inc, T36E2	P41258	8	4	P41654	14	14

*Includes duds.

FUEL CELL FIRINGS (Continued)

	Gasoline Firing Record No.	Total Hits on Projected Area* Single Shot	Compound	Kerosene Firing Record No.	Total Hits on Projected Area* Single Shot	Compound
500 yards Front Below (Continued)						
20mm, HEI, M97	P41477	4	2	P41284		
20mm, HEI, M97				P41279	8	23
20mm, Inc, M96	P41636					
20mm, Inc, M96	P41637			P41283		
20mm, Inc, M96	P41446	18	9	P41286	12	16
500 yards Rear Above						
Cal. .50, API-T, M20	P41074			P41261	7	18
Cal. .50, API-T, M20	P41247	14	19			
Cal. .50, Inc, M23	P41643			P41262		
Cal. .50, Inc, M23	P41647	17	16	P41470	15	19
Cal. .60, API, T39	P41078					
Cal. .60, API, T39	P41079			P41264		
Cal. .60, API, T39	P41087	18	8	P41475	12	25
Cal. .60, API, T39	P41248					
Cal. .60, Inc, T36E2	P42378					
Cal. .60, Inc, T36E2	P41089			P41263		
Cal. .60, Inc, T36E2	P41250	15	11	P41483	13	14
20mm, HEI, M97	P41091			P41269		
20mm, HEI, M97	P41090	14	11	P41280	21	11
20mm, HEI, M97	P41253					
20mm, Inc, M96	P42383					
20mm, Inc, M96	P40499			P41268		
20mm, Inc, M96	P41255	13	16	P41281	15	18
37mm, HE, M54	P41246			P41660		
37mm, HE, M54	P41260	15	1	P41450	6	4
1000 yards Front and Below						
Cal. .50, Inc, M23	P41805					
Cal. .50, Inc, M23	P41803	8	18	P41793	5	31
Cal. .60, API, T39	P41810					
Cal. .60, API, T39	P42411	7	10			
Cal. .60, Inc, T36E2	P41800					
Cal. .60, Inc, T36E2	P41818	15	9			
Cal. .60, Inc, T36E2	P42425					
20mm, HEI, M97	P41791					
20mm, HEI, M97	P41827	6	11			
20mm, Inc, M96	P42400			P41822	5	11
20mm, Inc, M96	P42403	10	1			

*Includes duds.

FUEL CELL FIRINGS (Continued)

	Gasoline Firing Record No.	Total Hits on Projected Area* Single Shot	Com-pound	Kerosene Firing Record No.	Total Hits on Projected Area* Single Shot	Com-pound
1000 yards Rear Above						
Cal. .50, Inc, M23	P41831					
Cal. .50, Inc, M23	P41776	9	16	P41779	4	19
Cal. .60, API, T39	S44229					
Cal. .60, API, T39	P42436					
Cal. .60, API, T39	P42437	20	18			
Cal. .60, Inc, T36E2	P41782					
Cal. .60, Inc, T36E2	P42441					
Cal. .60, Inc, T36E2	P42480	12	11	P41768	6	11
20mm, HEI, M97	P41786					
20mm, HEI, M97	P41695	9	14	P41709	6	11
20mm, Inc, M96	S44231					
20mm, Inc, M96	P42482	11	3	P41702	4	5
2000 yards Front and Below						
Cal. .60, API, T39	P41513			P41518		
Cal. .60, API, T39	P41494			S44247	14	34
Cal. .60, API, T39	P43109	19	15	P41624		
Cal. .60, Inc, T36E2	P41677					
Cal. .60, Inc, T36E2	P42798			P41635		
Cal. .60, Inc, T36E2	P42958	9	8	P41628	11	25
Cal. .60, Inc, T36E2	P43008					
Cal. .60, Inc, T36E2	P43069					
Cal. .60, Inc, T36E2	P43086					
20mm, HEI, M97				S44253		
20mm, HEI, M97				P41615	22	12
20mm, Inc, M96	P43168					
20mm, Inc, M96	P43311					
20mm, Inc, M96	P43350	52	41	P41505		
20mm, Inc, M96	P43378			S44252	9	14
20mm, Inc, M96	P43393					
2000 yards Rear Above						
Cal. .60, API, T39	S44238	5	7	P41670	11	7
Cal. .60, Inc, T36E2	P41682					
Cal. .60, Inc, T36E2	P41657	7	10	P41642	8	9
20mm, HEI, M97	P41661	6	11	S44246		
20mm, HEI, M97				P41650	9	22
20mm, Inc, M96	S44237	9	5	S44239	6	6

For A-35 and P-47 Empty Firings, See BRLM 437.

P-51

	Gasoline Firing Record No.	Single Shot	Com-pound
200 yards Front Below			
3 cm HE, Mk 108	P41965		
3 cm HE, Mk 108	P41970	5	4

*Includes duds.

FUEL CELL FIRINGS (Continued)

	Gasoline Firing Record No.	Total Hits on Projected Area* Single Shot	Com-pound	Kerosene Firing Record No.	Total Hits on Projected Area* Single Shot	Com-pound
500 yards Front Below						
Cal. .50, Inc, M23	P41842					
Cal. .50, Inc, M23	P41846	6	20			
Cal. .60, API, T39	P41863					
Cal. .60, API, T39	P41935	5	13			
Cal. .60, Inc, T36E2	P41848					
Cal. .60, Inc, T36E2	P41855					
Cal. .60, Inc, T36E2	P41857	8	5			
20mm, HEI, M97	P41957					
20mm, HEI, M97	P41960	5	7			
20mm, Inc, M96	P41946					
20mm, Inc, M96	P41949					
20mm, Inc, M96	P41955	7	23			
P-59						
200 yards Rear Above						
3 cm HE, Mk 108				P41669	2	3
500 yards Rear Above						
Cal. .60, Inc, M23				P41680	7	3
Cal. .60, API, T39				P41272	8	5
Cal. .60, Inc, T36E2				P41271	9	2
20mm, HEI, M97				P41275	5	2
20mm, Inc, M96				P41274	10	3

* Includes duds.

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ABSTRACT:

The effectiveness of incendiary ammunition against aircraft fuel systems is analyzed. The probability of obtaining a kill on an aircraft due to the vulnerability of its fuel system to incendiary projectiles is the product of the probability that a round perforates the tank, the probability that the projectile functions, the probability that the penetrating projectile ignites the fuel after functioning and perforating, the probability that the tank does not self-seal, and the probability that a resulting fire causes a kill to the aircraft. These various probabilities have been obtained as functions of striking velocity from firings of incendiary ammunition against gasoline and kerosene filled fuel tanks. Experiments under controlled conditions, designed to study the mechanics of fuel tank ignition, are described and preliminary results presented.

OVER

Fuel Tanks, ... Ammunition

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